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Geothermal Energy Potentials Exploration in Main Ethiopian Rift Valley in Corbetti with Gravity Method, Ethiopia.

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Abstract
In this Research work integrated geophysical techniques with gravity surveys method have been carried out over the Corbetti Caldera in the central Main Ethiopian Rift (CMER) to verify the geothermal potential of the caldera.The Corbetti Caldera is characterized by Quaternary volcano tectonic activity which is mainly silicic volcanism and a resurgent caldera structural system. The Quaternary volcanism is associated with a wide spread of steaming ground and fumarolic activity which evidenced the existence of a heat source at depth. 200 gravity data have been used and analyzed and results are presented as gravity counter map for qualitative interpretation. The complete Bouguer gravity anomaly map of the area indicates the existence of intrusion beneath the caldera, i.e. the highest Bouguer gravity anomaly resulting from the higher density of the intrusion. Based on the joint analysis of data from these geophysical methods and thermal manifestations in the area.

Keywords: *Gravity Surveys, Corbetti Caldera in the central Main Ethiopian Rift (CMER), Quaternary Volcano Tectonic Activity, Caldera, Geophysical Method.*

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I. Introduction

1.1. Background

Geophysics is the study of the earth by the quantitative observation of its physical properties. Since there are numerous geophysical methods the geophysicist must be able to choose the methods that are applicable in the area, cost effective and are able to give a solution to the problem at hand. The word geothermal comes from the Greek words geo (earth) and thermal (heat). So, geothermal energy is heat from within the earth and geothermal resources consist of thermal energy from the Earth's interior stored in both rock and trapped steam or liquid water. In its simplest terms, geothermal means earth-heat. It is related to the thermal energy of Earth's interior. We can use the steam and hot water produced inside the earth to heat buildings or generates electricity. Geothermal energy is a renewable energy source because the water is replenished by rainfall and the heat is continuously produced inside the earth.

Geothermal system is made up of four main elements namely, a heat source, a reservoir, fluid which is the carrier that transfers the heat and fluid path ways (e.g. faults and fractures). Parameters that characterize a geothermal system are temperature, porosity, permeability and chemical composition of the fluid. Our interest is in areas where we get high temperatures, high pressure, high porosity and good permeability and low content of dissolved solids and gases in the water. Many high-temperature (>180°C) hydrothermal systems are associated with recent volcanic activity and are found near plate tectonic boundaries (subduction, rifting, spreading or transform faulting), or at crustal and mantle hot spot anomalies.(fig.1.1).Intermediate- (100 to 180°C) and low-temperature (<100°C) systems are also found in continental settings, where above-normal heat production through radioactive isotope decay increases terrestrial heat flow or where aquifers are charged by water heated through circulation along deeply penetrating fault zones(fig.1.1). Under appropriate conditions, high-, intermediate- and low-temperature geothermal fields can be utilized for both power generation and the direct use of heat (Tester et al., 2005).Geo-thermal energy is one of the rare forms of energy which is not directly or indirectly from solar energy. In areas where hot springs are found, hot springs baths are very common and enjoyable form of recreation. However, they need to be in a controlled environment since they cannot be accessed without proper supervision. We have earlier seen how it is harnessed, the process involved is a long and expensive one and not feasible in some areas.

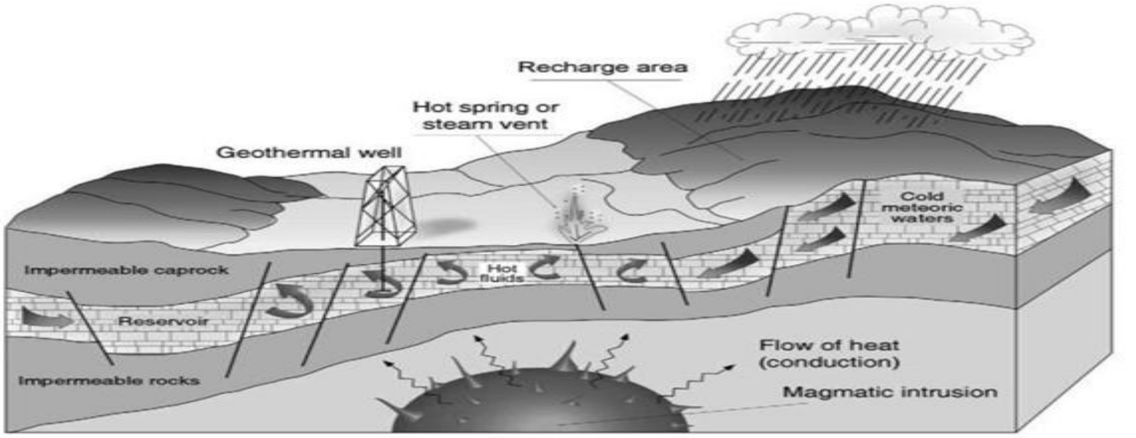


Figure 1.1A geothermal steam field with its elements: recharge area, impermeable cover, reservoir and heat source.(Enrico Barbier 2002

Geothermal energy can sometimes find its way to the surface in the form of: volcanoes and fumaroles (holes where volcanic gases are released) hot springs and geysers. When magma comes close to the surface it heats ground water found trapped in porous rock or water running along fractured rock surfaces and faults. Such hydrothermal resources have two common ingredients: water (hydro) and heat (thermal). Naturally occurring large areas of hydrothermal resources are called geothermal reservoirs.

Geological, geophysical and geochemical surveys have remained to be the main survey types carried out for the assessment of the geothermal resource potential of the East Africa continental rift zones. Occurrences of geothermal resources associated with the central volcanoes in the Main Ethiopian Rift (MER) which forms one segment of the East Africa continental rift zones can be intensively studied using geological (structural mapping), integrated geophysical (gravimetric, magnetic, electrical, etc.) And geochemical (water and gas analysis) method. The Corbetti volcano which forms one of the central volcanoes in the MER is the study area considered in this project. Previous works performed to assess the geothermal resource potential of the Corbetti included geological (structural mapping), geochemical (water and gas analysis) and geophysical (mainly gravity and electrical resistivity) investigations where magnetic data is lacking. Based on geological (volcanological, stratigraphy, etc.) and geochemical evidences, the evolution of the Corbetti volcano is determined to be associated with extensive fractional crystallization of parent mantle- derived basaltic magma occurring in a huge shallow level magma chamber. Fumaroles, steaming and warm grounds are some of the hydrothermal manifestations in the Corbetti Caldera (Elias Altaye, 1983). This research work study aims at the application of gravity method for detailed geothermal resource investigations of the Corbetti. The study stems from the necessity to make effective use of geophysics based on modern data analysis and interpretation knowledge for geothermal exploration. The outcome of the study may provide vital information to decide on the possibility of extending geophysical investigations for the assessment of the geothermal potential of the central volcanoes in the MER and for further scientific studies of rifting processes within the framework of global plate tectonics.

1.2. Location of the study area

The Corbetti geothermal prospect area is one of the geothermal prospect areas identified in the MER and the Afar depression (Fig. 1.3 A). It is located in the central part of the MER and approximately lies between latitudes 6.880N - 7.750N and longitudes 38.000E - 39.000E and about 250 km south of Addis Ababa along the Addis Ababa - Nairobi highway. The Corbetti geothermal prospect area encompasses an area of about 12100 km2 within which Urji`, Chebbi, Danshe and other volcanoes are consisted. The Corbetti caldera that constitutes the present study area is bounded by Lake Hawassa to the south and Lake Shalla to the north, with geographic locations between latitudes 7.170N - 7.250N and longitudes 38.300E - 38.470E (Figure 1.3 B).

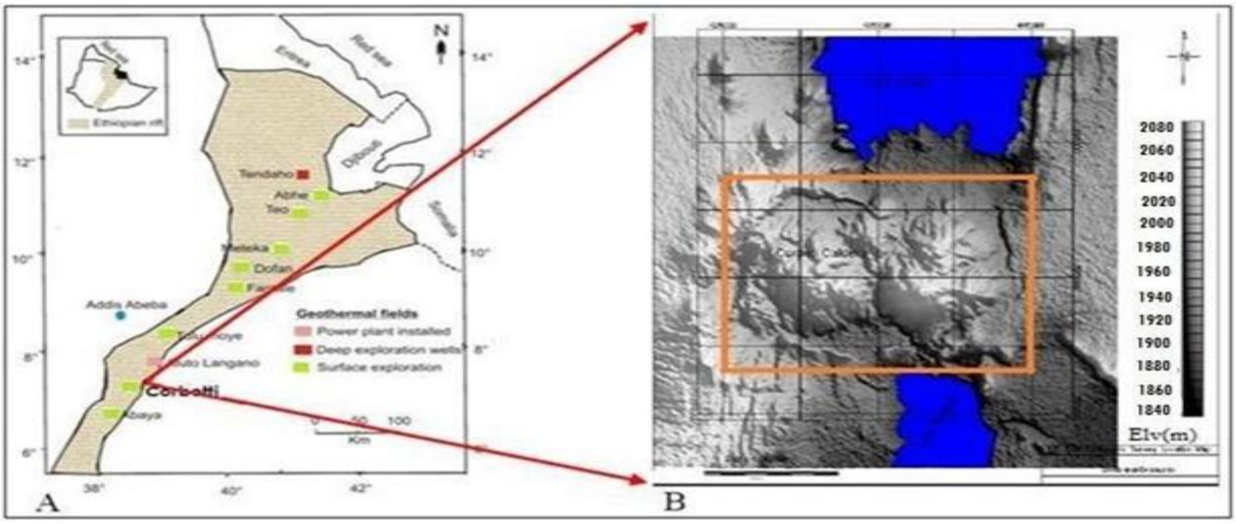


Figure 1.2A: Location map of Corbetti, B: Shaded relief elevation map of Corbetti (MME, 2008).

1.3 Objectives

1.3.1 General Objective

The general objective of this senior project is to properly utilize and analyze the present geophysical studies and integrate them with the previous geophysical and geological study results in order to delineate and map the prominent geological features, structural features and volcanologic features of the Corbetti caldera that are thought to be the controlling factors in the assessment of geothermal resources.

1.3.2 Specific objective

- ✓ To map the structural patterns, lithologic outcrops of the study area
- ✓ To Estimate geophysical properties of the geothermal system.
- ✓ To identify and locate exploitable reservoirs on the map.

1.4. Methodology

To achieve the above objectives the following methodology has been conducted.

(a) Data collection

The first step in any research is to identify the data/information required to solve the proposed problem for this study the following data's are needed and collected

- ✓ Geological map
- ✓ Geographical map
- ✓ Geomorphological map
- ✓ Hydrological map
- ✓ Satellite imageries
- ✓ Arial photo
- ✓ Geologic reports

(b)Data Analysis

The above collected secondary data are analyzed based on the proposed objectives and the required information was generated.

(c)Result interpretation

After analyses have been carried out the final results are interpreted and recommendation was given.

1.5 Review of Previous Work

The Corbetti has been studied for different purpose since (Mohr, 1966) and Macdonald and Gibson (1969). But the initial stage of the geothermal exploration started by the joint studies of the EIGS and the UNDP technical teams (UNDP, 1973). Then followed by Lloyd, 1977, which indicated the presence of a geothermal resource and recommended future detailed geoscientific study which includes among others, detailed geological and surface hydrothermal alteration study on 1:50,000 and 1:20,000 scales. Detailed geological and surface hydrothermal alteration study on 1:50,000 scales were conducted by Elias Altaye (1983-1984). Temperature measurements and associated hydrothermal alteration studies in Corbetti geothermal prospect are carried out by MoME and GSE, 2011. The present study is a continuation of the above studies.

II. Review Of The Geology And Tectonics Of The Main Ethiopian Rift

The Main Ethiopian Rift (MER) is a roughly NE-trending sector of the East African Rift system that includes a series of rift segments extending from the Afar Depression at the Red Sea-Gulf of Aden intersection to the Kenya Rift. The MER is characterized by active extensional tectonics accommodating the ~6-7 mm/yr. relative movement between the African and Somalian plates. Generalized regional synthesis indicates that the MER has evolved from the development of half grabens with opposing polarity in the early rifting phase (Oligocene to early Miocene) to full symmetrical grabens in later stages. The rift basins, which are contiguous but separated by transfer or accommodation zones, have variable strike lengths (ranging between 50 and 100 km) and widths over the area of the rift sector. The MER has been traditionally differentiated into three main segments: (1) the Northern (NMER), (2) the Central (CMER), and (3) the Southern (SMER), representing different stages of the extension process, from early rifting in the Southern MER to more volutes stages in the Central and Northern MER preceding the incipient seafloor spreading in Afar. Geophysical (gravity and seismic) investigations suggest more than 3.5 km of sedimentary fill within the basins. This may warrants exploring for oil and gas within the basins. The Great East African Rift itself is part of the Afro-Arabian Rift system that extends for about 6500km from Turkey to Mozambique (Mohr, 1962). Flood basalts erupted primarily between 31 –29 Ma cover much of the Proterozoic basement, extending over an area of the Ethiopian plateau ∼1000 km in diameter (Baker et al., 1996; Hofmann et al., 1997; Ukstins et al., 2002). A mantle slow-velocity anomaly underlies the rift (Bastow et al., 2005; Benoit et al., 2006; Montelli et al., 2006) down to at least 650 km depth beneath Afar and rising to at least 75 km depth beneath the Main Ethiopian Rift. The shallow part of this anomaly is offset ∼25 km from the rift axis (Bastow et al., 2005) and dips westward, possibly connecting to the African Super plume (Benoit et al., 2006) although direct evidence remains elusive.

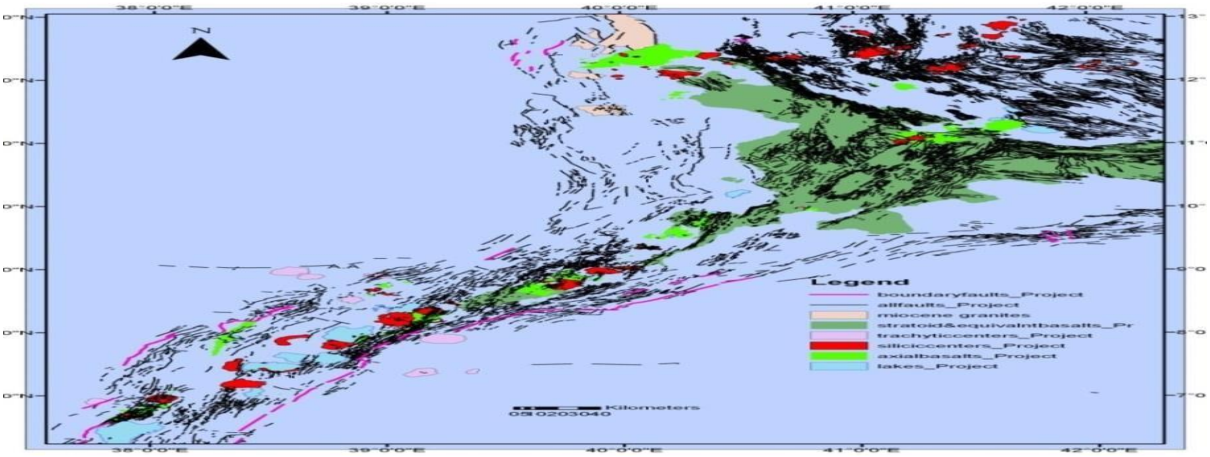


Figure 2.1.Geologic sketch of MER & Afar from satellite image.

2.1. Geological and structural Setting of the study area

The closed basin of the nested Hawassa Corbetti caldera complex is a giant elliptical depression 30-40kms wide. It is a Holocene volcanic complex found in the central sector of MER and located 250km. southern Addis Ababa. Most abundant volcanic rocks of Corbettiare peralkalinepyroclastics (ignimbrite and pumice)(DI PAOLA, 1972). Several NNE trending minor normal faults cut all the volcanic rocks within the caldera except the youngest products of the urji and chabbi centers. Eight shallow bore holes were sink at different locations in and outside the caldera ranging in depth from 50m-200m. the bore holes were irregularly located but have enabled constructing shallow subsurface volcanic stratigraphy. Altered rock forms a roughly north-south elongated area some two kilometers long and several hundred meters wide. Steam activity is apparent only along the extremities of this zone, but it is possible that thick soil cover may have masked the rest of the area

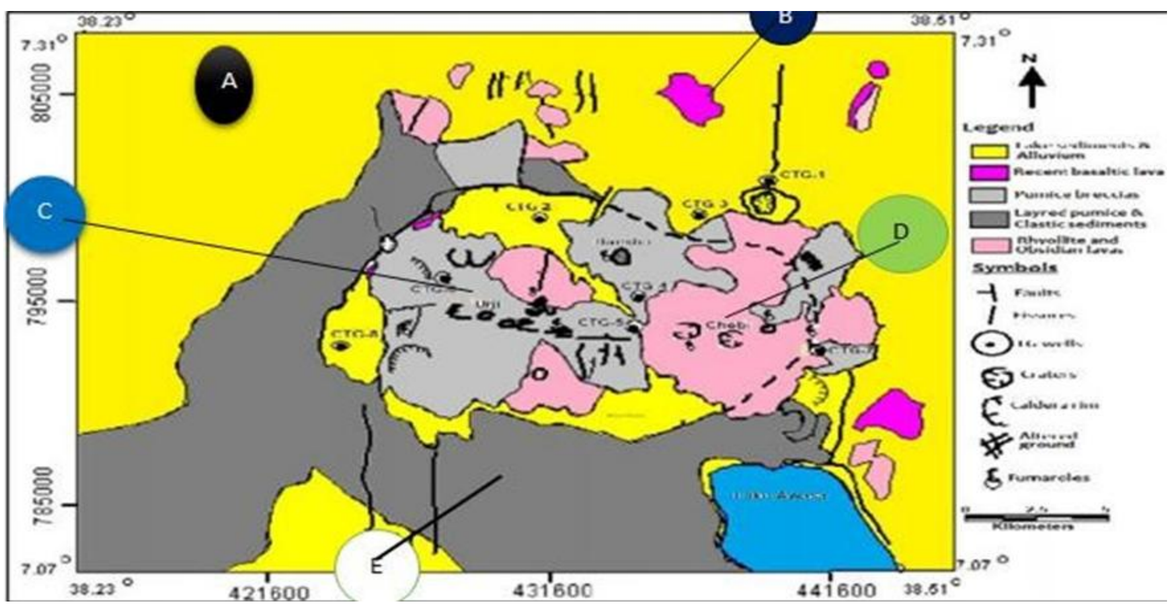


Fig 2.2 Simplified geological map of Corbetti area (modified from TadesseMamo and ZewduAbtew, 2011) Chebbi volcano is extruded from the eastern segment of the caldera ring fractures, but east west tectonics may also be an important factor controlling its location. The east west alignment evident on Urji is even more evident on Chebbi because the pyroclastic over burden is less or absent. Present east-west sub-parallel fissure swarms cut the lava flows independent of their flow direction and are probably the surface expression of deep tectonic weakness evidenced also by a major east-west fault, down thrown south, which appears east of Chebbi and gains topographic expression east wards (UNDP Technical Report, 1973). There are many occurrences of fumaroles (steam vents) and hot ground (hot springs) in several places within the caldera. In general most of the hydrothermal manifestations are associated with recent volcanological fractures such as eruption centers, craters and caldera rims, controlled by structural features (faults, fissures, joints and contact zone). Hydrothermal manifestations i.e., altered ground with fumarolic activities are associated with fissures, craters, faults and caldera rims, where tectonic structures give major access for hydrothermal fluids. These zones of fumeroles and structural features are supposed to be favorable zones for potential mineral deposit like epithermal Gold, Sulfides, etc. and also geothermal resource area which usually are zone of alterations. Corbetti is a silicic volcanic system similarly to Alutu volcano, except for it's being a well-developed resurgent cauldron system. Corbetti caldera has an irregular elliptical outline, elongated in the east-west direction and measuring 10 and 15 km along its two axes. The eastern rim of the caldera is missing, most likely due to the eastern part of the parent volcano having been completely removed during caldera formation. Later ignimbrites, which led to the collapse of the caldera, form the present rift floor surface in the area and the flanks of the caldera that are still intact. On the volcanic edifices situated inside the caldera, fissures oriented in the E-W direction cross, NNE-SSW trending regional rift forming faults. The results of geological study could be summarized as follows: The volcanic products at Corbetti are very young. The repeated cycle of volcanism forming the present morphology of Corbetti system normally shall have remnant magma intruded at shallow depth. This young and shallow magmatic chamber at shallow depth is providing the heat to the Geothermal System at Corbetti.

The study of hydrothermal alteration minerals on the cuttings recovered from the shallow wells showed the presence of high temperature mineral assemblages such as chlorite, kaolin, calcite and quartz (Kebede et al, 1987 as cited in MoME, 2008). The annular structural configuration of the caldera is complicated by the existence of a dense set of the rift forming faults in the NNE-SSW direction. Transversal E-W oriented fissures and the NNE-SSW rift forming faults control the occurrence of hydrothermal features. An extensive cap rock having large lateral coverage exists at Corbetti in the form of lake sediments and associated overlying pyroclastics. These cap rocks serve to prevent the heat of the Corbetti system from escaping to the surface, thus insuring a minimal cooling rate to the heating system. Corbetti is considered to be a classic resurgent cauldron system post-caldera volcanism during the Pleistocene having produced four major volcanic edifices Urji, Chabbi, Danshe and Borena. Urji occupies the center of the caldera. chabbi and Borena occupy an inferred eastern caldera rim, being products of post caldera resurgence of volcanism along possible ring fractures. Danshe and other low lying eruptive centers such as Hare and Guge probably stand on ring fractures skirting the interior of the caldera in the Northeast and west.

III. Theoretical Background Of the Gravity Method

3.1 Overview of the Gravity Method

Gravity meters measure the difference in gravity between a base station (where the absolute value of gravity is known) and a series of field stations. Most base stations are established by measuring the difference in gravity between the new base and an already established base station. Once the gravity at a new field site is known, theoretical gravity is calculated. Theoretical gravity depends on latitude, elevation, and on the surrounding topography.

3.2. Basic Principles of Gravity. *Gravimetry measures the variation in gravitational acceleration and is based on two well-known laws of physics-*

i. The Law of Universal Gravitation; $\vec{F} = -G\frac{m_1 m_2}{r^2}$ *(1)*

G – Gravitational constant = 6.67 □ 10-11 N-m2/kg2

ii. Newton's second law of motion; $a = \frac{\vec{F}}{m}$ *(2)*

a – acceleration

The Earth's mass can be treated as if its mass is concentrated at a point, at its center, and any object having a mass $\mathbf{m_o}$ *resting on the Earth's surface, will be attracted to the center by a force (its weight)-*

$$\vec{F} - G\frac{m_e m_0}{r^2}$$

$\mathbf{F = G\,[\,(m_e m_o)\,/\,R_e^2\,]}$ ***...****{3}*

$\mathbf{m_e}$ ***– mass of the Earth,*** $\mathbf{R_e}$ ***– average Earth's radius***

If the object is lifted a short distance and allowed to fall, the acceleration due to gravity: $\mathbf{a = F/m}$ □$\mathbf{g = F/m_o}$□$\mathbf{Gm_e/R_e^2}$ ***[gal] or [mill gals]. ..****{4}*

The magnitude of gravity on the earth's surface depends on:

Latitudeelevation of the measuring pointtopography of the surrounding terrain Earth tides andvariation in density from exploration point of view, the magnitude of the gravitational field caused by variation in density is the most significant factor although, its effect is much smaller when compared to the other four factors. The variation in g from equatorial to Polar Regions, for instance, amounts ~ 5 gals or 5% of 980 gals, whereas, the gravity anomaly in most exploration works rarely exceeds 10 mgals. Moreover, the variations in g in exploration (caused by density) are generally very small as compared to the effects of large changes in latitude and elevation. Fortunately, these effects can be removed, with a good accuracy, from the measured data during reduction.

3.3. Gravimeters

*The mechanism of modern gravimeters are based on the attraction exerted on a very small mass (few milligrams), by the Earth's gravitational field. These gravimeters are essentially very sensitive mechanical balances in which a mass is supported by a spring. Small changes in "g" moves the weight against the restoring force of the spring. Since, the displacement of the spring (**δs**) is very small, Hook's law applies; i.e., the restoring force is proportional to the change in length.*

$\mathbf{F = M\delta g = K\delta s}$□$\mathbf{\delta g = (K/M)\delta s}$ ***...****{5}where K – is a spring constant in dynes/cm. The stable type of instrument, which has a linear dependence on gravity over a large range, requires substantial amplification of the small change in length of the spring. In order to measure* ***δg*** *to 0.1, for instance, one must detect the change in spring length of the order of 1/10 since,* ***δg/g□δs/s*** *and that is why we need the artificial magnification. The amplification may be mechanical, optical, electrical or the combination of these.Mechanically, we can make K/M small, by using large mass and weak spring. But, the enhancement in sensitivity is very limited. Alternatively, the period T, of the system is;*

*T = 2□□(**M**/K) □ K/**M** = 4□*^{2} */* $\mathbf{T^2}$*. Substituting this in {5},* ***δg*** *= 4□*^{2} $\mathbf{\delta s/T^2}$ ***...****{6} Thus the larger period, the better its sensitivity but, requires longer measuring time.*

3.4 Gravity and Figure of the Earth

Theoretically, it is possible to calculate the earth's figure by assuming the earth as a spherical mass of fluid, rotating about its polar axis, and having density increasing with depth, figure. The surface of such theoretical shape is an equipotential of the gravitational plus the centripetal force fields.

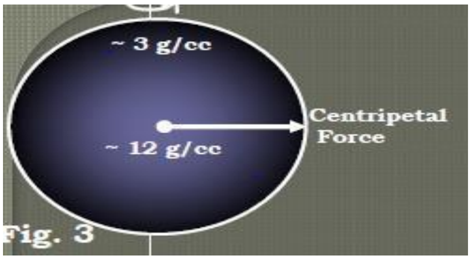


Fig. 3

3.4.1 The reference spheroid

The reference spheroid is the surface of the earth defined as a mathematical figure in terms of the gravity values at all surface points. It is considered as an equipotential surface, representing mean sea level, that can virtually be obtained by removing the excess continental mass that rise above and, filling the oceanic depressions which sink below it. Hence, the orientation of the gravitational force, everywhere on this surface, is normal; or in other words, the plumb-line is vertical at all points.

*The formulae, adopted by International Association of Geodesy (I.A.G) in 1967, gives the value of **g**, at any point on the spheroid surface as:*

$g = g_o(1 + \alpha \sin^2\phi + \beta \sin^2 2\phi)$,**...**{8} go = equatorial gravity = 978.0318 gals

ϕ = Latitude, α = 0.0053024, β = -0.0000058

3.4.2 Geoid

Neither the mathematical surface (reference spheroid) nor the geodetic surface (geoid) considers the lateral variations in density. When these occur close to the surface, they are the object of gravity prospecting, in exploration geophysics. Even in its finest form, equation 8 (the expression for g on the reference spheroid) is somehow a crude approximation since, it neglects the undulations on continental surfaces and ocean floors. In fact, the continental land masses have a mean elevation of about 500m while, the mean depression under the oceans is in the order of 9000m, all measured from the mean sea level. The true sea level, however, is influenced by these irregularities and accurate measurements of elevations should therefore take this in to account. Geodesists define a practical sea level (an equipotential surface) through careful measurements of g, that takes the above point in to consideration. This surface is known as geoid and is defined as average sea level over the ocean's surface and would lies in a canal, say, cut through the continental land masses Obviously, the geoid an the reference spheroid do not coincide as the former wraps upward, under the continents and downward over ocean basins. Nonetheless, this difference seldom exceeds 50 m.

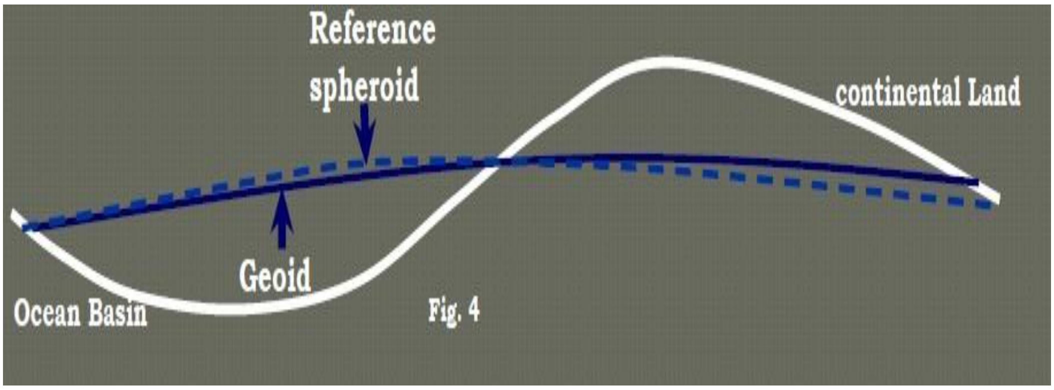


Fig. 4

Neither the mathematical surface (reference spheroid) or the geodetic surface (geoid) consider the lateral variations in density. When these occur close to the surface, they are the object of gravity prospecting, in exploration geophysics.

3.4.3. Data Reduction

Gravity data are generally affected by several factors and must be corrected for such variations as instrument drift, latitude, elevation; in order to reduce to the value they would have on some datum plane (for e.g., geoid) *or some other surface everywhere parallel to it. The following are essential components of the gravity data reduction:*

***a) Drift correction**:- results from creep in the springs of the instrument despite, temperature stabilization. • Common drifts rates 0.01 – 1 mgal/hr.*

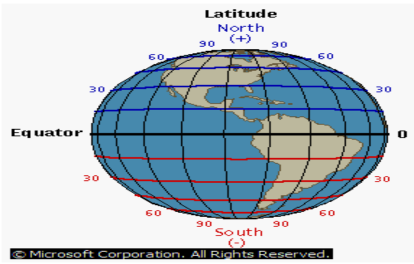
- *Means of correction hourly visit to the base station.*
- *Sense of correction positive drift requires negative correction and vice-versa.*

***b) Tidal correction**:- related to the gravitational attraction of the Moon and the Sun.*

- *Maximum amplitude of variation ~ 0.3 mgal.*
- *slow and quasi periodic*
- *Means of correction - normally together with instrument drift.*

c) Latitude correction

The combined effect of the earth`s rotation and its equatorial bulge produces an increase in the value of g with latitude. g increases from 9.78 m/s2 at the equator to 9.83 m/s2 at the poles. dgL/ds□ 1/Re (dgL/d□) □ 1/Req (dgL/d□) □ 0.81sin(2□) mgal/km, N-S of the base. where, □ = geographic latitude,Re = radius of the earth at latitude □,and Req = equatorial radius.Since gravity increases with latitude (both N and S), the above correction is always additive a one goes towards the equators.



d) Free-air correction

The gravitational attraction decreases with elevation since, it varies inversely with the square of the distance from earth's center. Hence, it is necessary to correct the reading so that all field readings are reduced to a datum surface.

Dg/dh = -0.308 mgal/m where, h = elevation in m.

The free-air correction is added/subtracted to the field reading depending on weather the station lies above/below the reference datum. This is the most critical one in gravity data reduction. ±5 m accuracy in elevation implies an error of± 1.5 mgal in g.The free-air correction takes no account of the material between the station and the reference plane.

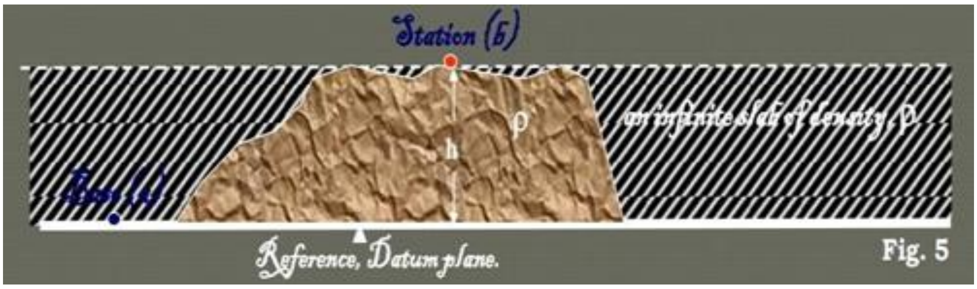
e) Bouguer correction

The Bouguer correction accounts for the gravitational attraction due to materials between the station and the datum plane, which has been ignored in the free air.

Δg/Δh = 2πG□= 0.04188 □mgal/m where, h = elevation in m.

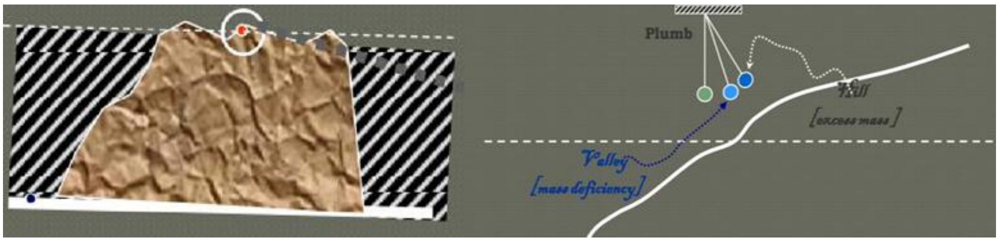
And □ = density in g/cc □ 2.67 for common crustal rocks

The Bouguer correction is subtracted/added to the field reading depending on weather the station lies above/below the base at the reference datum. It is therefore of opposite to that of free-air.



f) Terrain correction

Also known as topographic correction and takes care of surface irregularities in the vicinity of the measurement point. This refers to hills (excess mass), above and, valleys (mass deficiency), below the point of the hypothetical surface used for the Bouguer slab.



*Both topographic features affect the gravity measurement in the same sense, i.e., reducing the readings due to upward attraction by the excess mass of hills or mass deficiency (less attraction), due to valleys. Terrain corrections are, therefore, always **positive**. One method of carrying out terrain correction is to divide up the area around a station into sectors bounded by concentric circles of radii drawn at suitable angular intervals. For such arrangement the correction term is given as;*

$$\Delta gT = T\rho = G\rho\phi | \, r2 - r1 + (r1^{2} + z^{2})^{1/2} - (r^{2} + z^{2})^{1/2}$$

T = Terrain factor, ρ = density, ϕ= angular interval for sectors, [rad], r1, r2 = inner & outer radii of the sectors, Z = mean elevation

G = 6.67 × 10^3 for Δg in mGal and ρ in g/cm3 (t/m3)

3.4.4. Bouguer Anomaly

The Bouguer gravity anomaly is obtained after all the preceding corrections have been applied to the observed gravity. Terrain correction is not always applied. When applied, it is termed as complete Bouguer anomaly. If not it is known as simple Bouguer anomaly. gB□gobser□gd□dgL□dgFA□dgB□dgT

The difference between the observed and theoretical gravity is called the Bouguer anomaly. If the Bouguer anomaly is negative, it means the observed gravity is less than the theoretical. Because the force of gravity is proportional to the mass responsible for the gravitational field and inversely proportional to the square of the distance between any part of that mass and the observation point, a local lack of normal mass (say, a thick layer of low-density sediments instead of heavy igneous rocks of negligible porosity) will result in a local gravity low.

IV. Acquisition, Processing, presentation and interpretation of the Gravity Data

The gravity data employed in this study are obtained from the Geological Survey of Ethiopia (GSE), department of geophysics and the instrument which is used to collect the data is Lacoste & Romberg gravimeter. A total of 200 observations are employed for this project and were treated by a homogeneous reference to the IGSN 71 datum. The theoretical gravity, at a given latitude, has been calculated using the 1967 gravity formula (Geodetic reference system 1967; Moritz, 1971). Positions (latitude and longitude) and elevations of the gravity stations are determined by GPS (Global Positioning System) and altimeter measurements. The Free-air and Bouguer corrections were applied according to the theoretical schemes discussed in the previous sections. A uniform reduction density of 2.67g/cm3 is used to compute the Bouguer anomalies. The computed Bouguer anomaly corresponds to complete Bouguer anomaly for all stations. Therefore, it is the complete Bouguer anomaly that has been considered in this work. Map presentation and *processing, including the preparation of upward continued map from the complete Bouguer anomaly map, and separation of residual components from regional performed by reducing (removing) upward continued map from the observed gravity anomaly map using Geosoft (Oasis Montaj) software. The end result of the gravity work in the present study is a compilation of complete Bouguer anomaly map, regional gravity anomaly map and residual gravity anomaly map that includes the area of interest, using the point gravity anomaly values computed at each observation points. The computed free-air anomaly values are plotted side by side to the point elevation of each station and presented as surface image map. The upward continued gravity map, the complete Bouguer gravity anomaly map and also the residual gravity anomaly map that shows local gravity anomaly are plotted as shown in the preceding sections.*

4.1. Free-Air Gravity Anomaly and Topographic Map

The free air anomaly map Figure (4.1b) shows a strong correlation with local topographic map Fig (4.1a), as shown in the Figure (4.1b), The Free-air anomaly map shows its maximum, about 45mgal and its minimum -2mgal in the study area of interest, i.e., the Chebbi and Urji volcanoes are the highest elevated areas of Corbetti caldera which is about 2100m a above msl and the volcanoes are associated with maximum Free-air anomaly which is about 45mgal

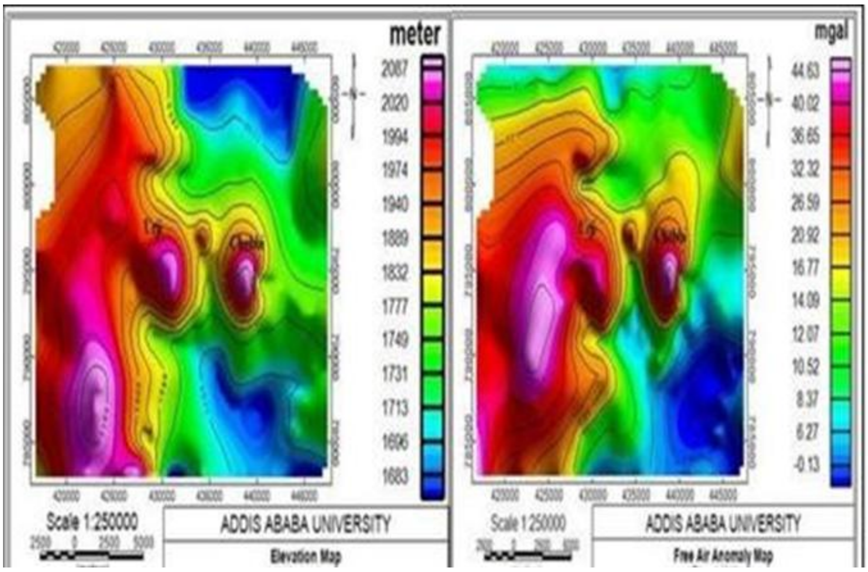


Figure 4.1 Topographic maps (A) and Free-Air anomaly (B) of the Corbetti Caldera and its surroundings.

The corresponding region on the topographic map Figure (4.1a) is delineated as higher elevation about between (1900-2100) meters which is associated with the central parts of the caldera and lower elevation values of (1600-1750) meters associated with the local depressions lying on the eastern parts of the elevation map.

4.2. The Complete Bouguer Gravity Anomaly Map.

The main end-product of gravity data reduction is the Bouguer anomaly, which should correlate only with lateral variations in density of the upper crust and which is of most interest to applied geophysicist and geologists.

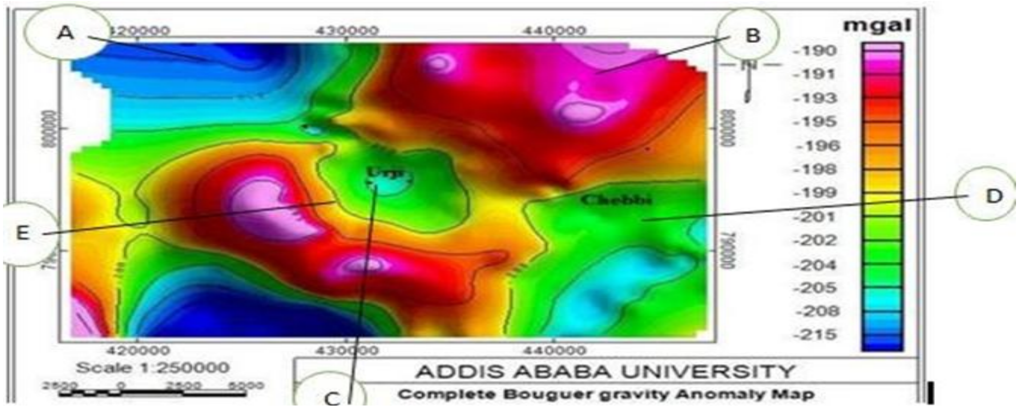


Figure 4.2 Complete Bouguer anomaly map of the Corbetti Caldera and its surroundings.(Kebede B,2014).

Referring to the complete Bouguer gravity anomaly map Figure (4.2), which is correlate with lateral variations in density of the upper crust beneath the study area. Generally, the magnitude of the Bouguer gravity anomaly values beneath the study area varies from minimum of -217 mgal to the maximum of -190mgal. Moreover, the anomaly map shows different contrasting anomalous zones (for example, a circular low of about -200 mgal having a steep gradient located at the center of the anomaly map) has outlined the geologically inferred Corbetti caldera.

The minimum gravity anomaly observed over the Chebbi and Urji volcanoes may be due to the reflections of the maximum elevations of the Chebbi and Urji volcanoes as compared to the anomalous zones observed over the rest of the Corbetti caldera and its surroundings. Observing to the complete Bouguer gravity anomaly map Figure (4.2), the gravity anomaly acquires a maximum value to the NE and SW of the Corbetti caldera. The NE part of the caldera generally coincides with a high gravity anomaly value of (- 192mgal to -187mgal) and the SE part which appears like a curve running from SE to NW below the caldera coincides with a high gravity anomaly value of (-193mgal to - 190mgal). This gravity highs may be interpreted as the effect the high density materials coming from the mantle during the formation of the caldera. The Southwestern and north western parts of the Corbetti caldera coincide with a minimum value of gravity anomaly (-207mgal to -217mgal) as shown in the complete Bouguer anomaly map. These gravity minima may be interpreted as the effect of low density crust materials. In general the Corbetti caldera is associated with a high gravity field with slight modifications imposed by the effect of the Chebbi and Urji volcanoes which are relatively associated with low gravity field in the study area. This is due to the fact that the Corbetti caldera consists of mantle derived materials of denser intrusions which come closer to the surface during the volcanic activities.

4.3. Upward Continued Gravity Anomaly Map

The upward continued gravity anomaly map Figure (4.3) is prepared using GM-SYS-3D model from the complete Bouguer gravity anomaly map by Geosoft Ware Oasis Montaj. The upward continued gravity anomaly map reflects the gravity anomaly of crustal masses buried at approximate depths varying from 15km up to the Mho depth.

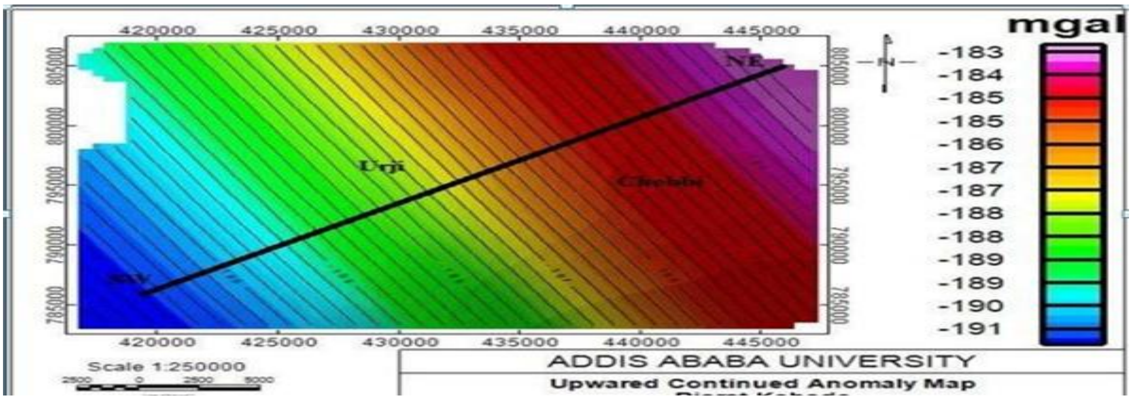


Figure 4.3 Upward continued gravity anomaly map of the Corbetti Caldera and its surroundings (from thesis, Kebede B.2014).

Referring to the upward continued gravity anomaly map Figure (4.3), the anomaly values contentiously increase as one goes from the southwestern to the northeastern part the study area. The upward continued gravity anomaly map shows the gravity anomaly of deep origin. The continuous gravity anomaly increment without interruption from SW to NE towards the axial portion of the Main Ethiopia Rift (MER) may be interpreted as being caused by the decrease of the crustal thickness of the region along the axial portion of the Main Ethiopia Rift (MER). Along the axial portion of the MER, denser mantle materials approaching closer to the surface has an enormous effect on the gravity field generated beneath the study area.

4.4. Bouguer Residual Gravity Anomaly Map

Usually it is very difficult to recognize the gravity effect of smaller or shallower features on gravity maps compiled on a regional scale with those of deep-seated structures and geological materials. Hence, it is very important to compile. Bouguer residual gravity anomaly map that predominantly reflect effects of local-scale or shallower features. The Bouguer Residual Gravity Anomaly Map Figure (4.4) is compiled by subtracting the upward continued gravity anomaly map Figure (4.3) values from the complete Bouguer gravity anomaly map Figure (4.2) values using the Geosoft software Oasis Montaj.

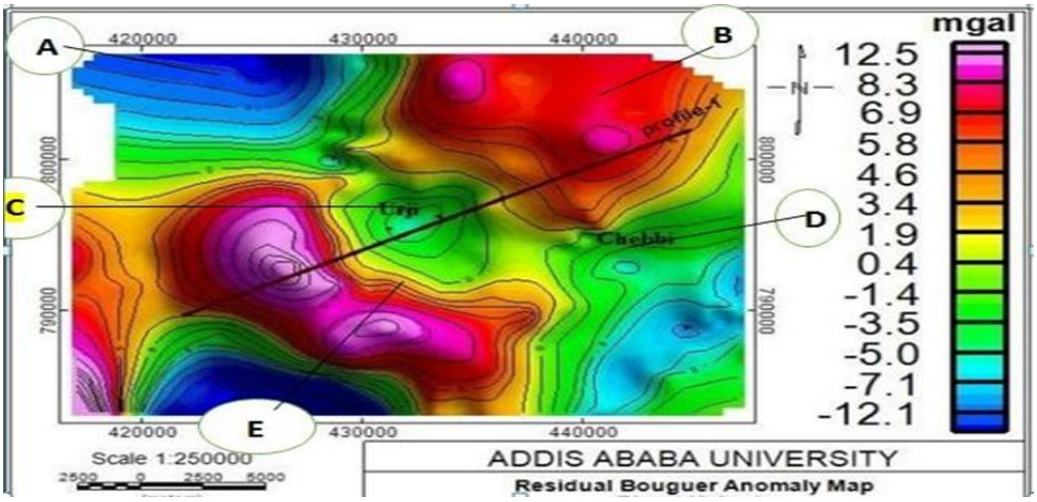


Figure 4.4Bouguer residual gravity anomaly map of the Corbetti Caldera and its surrounding The residual Bouguer gravity anomaly map Figure (4.4) of the study area generally varies locally from -14mgal up to 12mgal. Local positive and small negative gravity anomalies which are related to denser intrusions and low density materials are observed on the map. On the residual Bouguer gravity anomaly map Figure (4.4), the circular negative gravity anomaly located at the center of the anomaly map outlines the Corbetti Caldera and the sharp gravity gradient flanking the circular negative anomaly outlines the rim of the Corbetti Caldera. The Urji and Chebbi volcanoes are associated with local negative anomalies of about -6mgal. The cause for these negative anomalies may be the reflection of their higher elevations (2100m a.m.s.l). The other possible cause of these local negative anomalies over the elevated area of the Urji and Chebbi volcanoes may be interpreted as being caused by the rock types residing in the study area.

Referring to the geologic map of the study area Figure (2.1) the Urji and Chebbi volcanoes are composed of thicker low density formation (pumice) as compared to the other parts of the caldera. These thick low density geological formations account for the observed local negative residual anomalies (-4mgal up to -7mgal). With the exception of the negative anomalies observed over the elevated areas, it may be considered that the whole caldera is within a positive local gravity anomaly. The local positive gravity anomalies (9mgal-12mgal) in the study area are interpreted as being caused by a dense intrusion driven from the mantle to the crust by volcanic activity. The NW and SW parts of the caldera are associated with high negative anomalies (-12mgal up to -14mgal). According to the report of the MoME (1986), a geological structure (graben) with a thick infill of lake sediments and alluvium is assumed to be the cause of these local gravity lows.

Summery about the anomaly maps

Table 1. the relationship of the lithology with elevations, free air anomaly, complete Bouguer anomaly and residual gravity anomaly to interpret their potentials of geothermal energy in Corbetti by referring figure 4.1, 4.2, 4.3, 4.4at point A, B, C, D and E

numbers	Lithology	Elevations(m)	Complete Bouguer anomaly(mgal)	Free air anomaly(mgal)	Residual gravity Anomaly(mgal)	Coordinate
1	Alluvium	1940	-215	12.07	-12.5	805000N,420000E
2	Recent basaltic lava	1683	-191	10.52	6.9	805000N,440000E
3	Pumice breccias	2057	-202	40.02	-1.4	797500N,432500E
4	Layered pumice and clastic sediments	2022	-198	36.65	1.9	790000N,430000E
5	Rhyolite and obsidian lavas	2057	-204	40.02	-3.5	795000N,442500E

Referring table 1 by taking five points (lithologies),A,B ,C, D, and E from the geological map of the study area(fig 2.1) describe as following;

Free air anomaly and the elevations are directly proportional i.e. when the value of the elevation increase at the time the value of the free air anomaly also increase at the same coordinate (see fig 4.1). Therefore free air anomaly is depend on the elevations. Although Bouguer anomaly and residual gravity anomaly are depend on the lithology types which means basic rocks have higher values(recent basal lava, -191mgal C.B.A, 6.9mgal R.G.A at point B northeast direction fig 4.2.and 4.4 respectively) But acidic rocks (pumice breccias and rhyolite have -202 and -204mgal and residual gravity anomaly both have 40.02mgal at point C and D fig 4.2 and 4.4 central part of Corbetti,urji and Chebbirespectively) ,and clastic sediments and lake sedimentary alluvium have also low values of residual gravity anomaly and complete bouguer anomaly as we have seen the values from the table 1 and map in northwest and south west directions. But due to the presence of clastic in sediment, the value of lake sedimentary alluvium has low complete bouguer anomaly and residual gravity anomaly(-215mgal, -12.5mgal at point A fig 4.2. and fig 4.4 respectively) than layered pumice and clastic sediments(-198mgal, 1.9mgal at point E fig 4.2 and 4.4). This is because of the density of the mineralogical compositions of the rocks, the temperature and the density of the rock which are different from the surrounding lithology of the Corbetti. Generally as I compare map of complete bouguer anomaly(fig 4.2) and map of residual gravity anomaly(fig 4.4), map of residual anomaly is more localized than map of complete bouguer anomaly because map of residual anomaly is free from regional gravity anomaly(deep seated body), and northeast and southwest parts of Corbetti has high value of residual gravity anomaly which indicates that along this directions the geologic structures are more responsible for the productions of high potential geothermal energy.

V. Conclusions And Recommendations

5.1 Conclusions

Corbetti caldera is associated with a high gravity field with slight modifications by the product of Chabbi and Urji volcanoes which relatively exhibit low gravity field in the vicinity of the study area. This is due to the fact that the Corbetti caldera consists of mantle materials of large denser intrusion which comes to the crust during the volcanic activities. The very high local as well as regional Bouguer gravity anomalies indicate the existence of intrusions at shallow and deeper depths beneath the caldera. When comparing the Bouguer anomaly map, we observe areas with very high gravity anomalies values. The local Bouguer gravity anomalies clearly define the caldera with a circular gravity anomaly and the caldera rim with sharp gradient of the local gravity anomaly.

The geophysical data used in this research is very restricted to the study area due to limitation of resources. Based on the joint analysis of these geophysical data and the existing dominant thermal manifestations toward the northern parts of the Corbetti caldera the study area in which the Urji and Chebbi volcanoes are nested toward the southern shores of Lake Shalla has large scale geothermal potential for further development from Centre of caldera.

5.2 Recommendation

As I have done this senior project, the area which is Corbetti has a high potential energy or geothermal energy to produce electricity for the whole country annually because it is found in main Ethiopian rift valley. But I did not get the chance to visit, collect and record data from this area to do the senior project due to limitations of resources and this is one of the drawbacks of school of earth sciences. I strongly advice for the coming senior project working student who has a chance to do in this area, school of earth sciences should fund budget for students in order to visit and collect data and also for well understanding their study area.

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