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GEOTHERMAL RESOURCE EXPLORATION IN
THE ABAYA AND TULU MOYE-GEDEMSA GEOTHERMAL PROSPECTS, MAIN ETHIOPIAN RIFT

COMPiled
BY

ABEBE AYELE
MESERET TEKLEMARIAM
SOLOMON KEBEDE

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ABAYA GEOTHERMAL PROSPECT

1. INTRODUCTION

1.1 GEOGRAPHY

1.1.1 LOCATION AND ACCESSIBILITY

The study area is situated and includes part of the southern part of the Main Ethiopian Rift (MER) and adjacent western escarpment between 6°30’ and 7°00’ N - longitude (Fig.1). It is part of the northwestern Dilla Sheet (NB 37-6).

The Abaya geothermal prospect is accessible along the Shashemene - Arba Minch asphalted road which crosses the western part of the study area. Other important secondary roads which descend down into the rift floor from this highway include the Sodo-Bedesa-Dimtu-Awassa road and the Humbo-Abela Fermicho-Abaya State Farm road. These roads are surfaced with scoraceous material and are fairly maintained, however show deterioration after the rainy seasons. Many other secondary roads exist in the intensely cultivated and densely settled parts with elevation above 1800 m.a.s.l along the escarpments and connecting the mechanized plantations along the Bilate River flood plain in the rift floor.

1.1.2 Physiography and Drainage

The western part of the study area makes the escarpment of the southern part of the MER and is faulted in a series of normal faults and slopes down from an average elevation of about 2000 m a.s.l. to 1169 m a.s.l. at the level of Lake Abaya. The Pliocene Damota trachytic volcano which rises to 2950 m a.s.l. and Saloko ridge west of Humbo town form major volcanic landforms on the rift escarpments.

The rift floor comprises of flat volcano sedimentary plains at an average altitude of 1300 m a.s.l and is characterized by a series of sub-parallel normal faults with predominantly NNE-SSW trend forming horsts and grabens within the rift. The plains are cut at places by steep sided river valleys. This belt of intense faulting and Quaternary volcanism represent the southern sector of the Wonji Fault Belt (WFB) which is the active axis of extension in the MER. Similar to other parts of the
MER this active belt of tectonism hosts several complex rhyolitic volcanic centers the most prominent one in the study area being the Duguna-Fango rising over 1000m above the rift floor. The latter has a base diameter of over 10 km and rises to an elevation of 2240 m a.s.l. Other smaller rhyolitic centers rising about 500 m above the general rift floor level include Chericha, SalwaDore, Hako, Donga (Simbura), Obicha and Werecha (enclosure- ).

The study area is part of a closed drainage system within the southern MER with all rivers and streams draining into Lake Abaya. The Hamesa River and its tributaries draining the western part of the study area into the Lake. The central and northern part of the study area is drained by Bilate River and its tributaries such as Bisare and Derba which form a delta at it confluence into the northern shore of Lake Abaya. The other important river is Gidabo, which drains the Eastern escarpment and the Southeastern portion of the study area. The Gidabo River also discharges into Lake Abaya forming a delta. Several minor seasonal rivers flow from the surrounding high grounds in the rift floor plain during times of flood. The large volume of suspended clay material derived from the red lateritic soils of the escarpments and the lacustrine sediments being carried into the lake has imparted a yellowish brown color to Lake Abaya.

1.1.3 CLIMATE, SOIL AND VEGETATION

Part of the study area, being on the western escarpment, belongs to the Weyna Dega agro-ecological zone whereas the study area in the rift floor proper belongs to the Kola zone. A warm and humid climate is typical of the Weyna Dega zone, having a mean annual temperature ranging between 17°C and 20°C and with annual precipitation as high as 1500 mm. The Kola zone has a mean annual temperature between 20°C and 25°C with daily maximum temperatures as high as 35°C during the dry season. With regard to precipitation the area on the escarpment can be considered as part of the humid zones in the country with a mean annual rainfall ranging between 1200 mm and 1500 mm. The June-September rainfall (Kiremt) ranges between 400 and 700 mm and the February-May rainfall (Belg) commonly range between 400 and 600 mm with about 200 mm of rain distributed in the rest of the year (EMA, 1988). The Kola zone in the rift floor, which is in the rain shadow of the escarpments, generally gets half this quantity of rain predominantly in the Kiremet season.
Most of the study area along the escarpments is mantled by a thick red lateritic soil. The area in the rift floor has a thick soil cover derived from the volcanogenic lacustrine and alluvial sediments, and less extensive dark brown soils has developed from the older basic volcanics. Soil erosion is a significant problem in the area and it is noticeable that an effort has been made to preserve the soil by extensive terracing and afforestation. The soil of the region is generally good agricultural soil, the quantity of precipitation being the determining factor on what kind of crops are being cultivated.

The Weyna Dega zone is intensely cultivated and has a high population density (over 300 p/km²) with a farming and pastoral system of the Enset Culture. The quantity of precipitation make the Weyna Dega zone a low crop risk zone and enable to produce cash crops such as coffee with enset, maize and a variety of legumes which provide the staple food. In the Kolla zone cotton makes the cash crop and maize and legumes make the staple food crops for subsistance farmers. The development of suitable irrigation systems has enabled to cultivate cotton, tobacco and fruits in the mechanized state farm in the rift floor. The natural vegetation where preserved is an open bush land and wooded grass land with particularly acacia trees in the Kolla zone in the rift floor and broad leafed forest in the weyna Dega Zone.

1.2 REVIEW OF PREVIOUS WORKS

The earliest geothermal exploration work in the Abaya geothermal prospect area was carried out by EIGS-UN technical team (UNDP, 1973). This reconnaissance study, which included geological, geochemical, geophysical and infrared surveys, was conducted in a broader area covering the whole Ethiopian Rift Valley.

Subsequent studies to evaluate the geothermal resource within the broader lakes district of the MER have indicated that convective hot water systems are contained beneath the Quaternary rift floor sediments and volcanic rocks. The latter form a caprock with heat being derived from the Quaternary rhyolitic volcanic complexes along the axis of the MER. The reservoir was inferred to be within the upper units of the Tertiary volcanic products (mostly ignimbrites) that are exposed on the eastern escarpments that have been down thrown into the rift floor (Lloyd, 1977). It is also
widely accepted that Quaternary tectonic movements along the axis of the rift created widespread secondary permeability and faulted the cap rock whereby a supply of hydrothermal fluid to surface manifestations is maintained.

The survey has led to the identification of a number of prospective areas in the region of which the Abaya geothermal prospect is one of the Southernmost one. The study at Abaya has identified the occurrence of several hot springs and fumaroles. Fluid geochemical analysis of the representative springs indicated a chemistry ranging from alkaline-chloride type to acid-sulfate type with invariable high CO₂ content. Silica geothermometer of the southernmost spring water along the NW-Abaya fault yielded a temperature of 177 °C while a Na/K ratio geothermometer indicated subsurface temperature of 265 °C (UNDP, 1973). The discharge spring "(spring #6)" on the northwestern shore of Lake Abaya having near boiling point temperature and siliceous sinter deposits is an alkaline chloride spring, the highest SiO₂ content (204 ppm) in the Lakes district.

For geothermal gas studies (Glover, 1976) sampled the most vigorous fumarole in the Lakes District which is located on the northwestern shore of Lake Abaya near an acid sulfate spring. The sample gave calculated equilibration temperatures based on H₂/CH₄ ratio – T-CH₄ = 169°C which is in reasonable agreement with quartz equilibrium temperature (177°C) for the nearby spring #6 (Glover, 1976). Based on the results obtained from empirical geothermometers (chemical and gas), Glover (1976) has recommended further geophysical study to be conducted in NW Lake Abaya prior to the Bilbo area. Isotopic study on the spring discharges from the study area show relatively homogeneous compositions with (δ¹⁸O, δD) value showing a source on the mean precipitation (-3, -9) line and is quite distinct from the local surface drainage (Hamesa and Bilate Rivers) which lie on the evaporation enrichment line (Fig 14, Craig, 1977). This study showed that only spring #6 show a well defined oxygen shift (2.3 permil) thus providing an isotopic evidence for a high temperature subsurface water rock interaction. On the other hand, the perched (steam heated) acid spring on the northwestern Lake Abaya hydrothermal field (spring #7) has a high δ¹⁸O, δD value on a trajectory from the source water with slope 2.5 which indicates subsurface kinetic evaporation at high temperature.
A team from EIGS-GEP in 1979 has studied a broader area of the Southern Rift Valley lying in between Lake Abaya /South/ to Lake Awasa /North/ and Dilla town /East/ to Sodo town /West/. The work comprised geological and geothermal studies together with the production of a 1:250,000-scale map. By studying the volcanic and tectonic factors that influenced the hydrothermal activity, the Northwest Abaya region area was recommended as a first priority area in further investigations. Consequently, Vertical Electrical Sounding (VES) and gravity surveys were conducted in the prospect (Tezcan et al., 1983). The result of the geophysical survey suggested that high enthalpy geothermal water brought up through the high resistivity basement caused a low resistivity anomaly west of the hot spring alignment on the northwestern shore of Lake Abaya.

2. GEOSCIENTIFIC INVESTIGATIONS

2.1 GEOLOGICAL EXPLORATION

2.1.1 OBJECTIVE AND SCOPE OF WORK

The objective of the geological mapping is to characterize the nature of all active and fossil hydrothermally altered grounds together with the preparation of a 1:50,000 scale geologic map the four subsheets and to do further detailed work at 1:20,000 scale in selected areas of the subsheets. The geological, structural and hydrothermal alteration mapping provides information on the nature of the rocks (cap rocks, reservoir rocks), the nature of the altering fluid, duration and age of the thermal activity, the existence of geological structures which might have controlled circulation of hydrothermal fluids and an overview of the size of the geothermal field. One of its main objective was to limit the size of the permit, to define and optimize the following program, which involves higher cost investigation methods (geophysical and temperature gradient survey).

2.1.2 METHODOLOGY

The geological field work in the area was conducted using 1:50,000 scale topographic base maps and 1:60,000 scale aerial photos covering most of the study area which were blown up to 1:20,000 scale in areas where active hydrothermal manifestations are reported to exist. Traverses were taken along the major and secondary roads crossing most of the study area to get an understanding of the general geology of the study area using the 1:250,000 scale geologic map of the Northern Lake
Abaya Region (E.I.G.S -GEP 1979). Representative samples were collected from all map units for petrographic studies. Zones of active hydrothermal alteration were singled out and located on the map for more detailed visits.

In all localities of active hydrothermal manifestation the type of alteration and mineralization were described, discharge of springs, and pressure of fumaroles were estimated., Temperature measurements were done using a maximum thermometer while pH of spring discharges were measured using a phanphea paper. Field observations were made in the vicinity to get the extent of hydrothermal alteration and structures that may control the distribution of hydrothermal activity. Petrographic analysis of the collected rock samples was conducted.

2.1.3 DATA PRESENTATION AND INTERPRETATION
The data presentation and interpretation of the geologic investigation will be discussed in the form of (i) Statigraphy and (ii) Hydrothermal Activity

(i) Statigraphy
In this section a brief description of the map units which outcrop in the study area is presented. The local stratigraphy in the study area includes both volcanic and sedimentary rocks. The exposed volcanic units from the oldest to the youngest are Pre-rift Basalts (Tb1) Chewkare ignimbrites (Tig), Damota Trachytes (Trt2), Quaternary ignimbrites (Qig), Quaternary older pumiceous pyroclastics(Qp1), Abaya rhyolites (Qr1), Tena Bilate basalts (Qb1), Quaternary younger pumiceous pyroclastics (QP2), Abela rhyolites (Qr2), Recent basalts (Qb2) and Seluwa Dora, Korke, Duguna Fango rhyolite Obsidian flows (Qr3). The sedimentary units include Pleistocene volcano-sediments (Ql1) Holocene lake sediments (Q12) and recent alluvium and fluviatile deposits (Qa1). The distribution of the stratigraphic units is shown in the enclosure- to-. The description of the stratigraphic units from the oldest to youngest is as follows:

(a) Pre-rift Basalts (Tb1)
Intensely jointed, hydrothermally altered and spheriodally weathered basalt outcrops on the southwestern part of the study area on the series of faults forming the western escarp of the graben where Lake Abaya is situated. This basalt flow is conformably overlain by an ignimbrite
flow. Previous workers have correlated this unit with Aiba Basalts, but its association with rhyolitic ignimbrites probably suggests a correlation with Jima Volcanics or the Main Volcanic Sequence which has an absolute K-Ar age range of 42.7-30.5 Ma (Davidson, 1983). This age seems to be more appropriate compared with the correlation made by the earlier workers. Like many exposures of the Jima Volcanics south of the study area, south west of Lake Chamo it has been reported that flood basalts overlain by a succession of ignimbrites (Trap Series) overlie the Precambrian Basement (UNDP, 1973).

(b) Chewkare Ignimbrites (Tig)

A succession of ignimbrite flows units exposed on the west Abaya fault which forms the western escarpment of the Chewkare Graben was mapped as Chewkare Ignimbrites (EIGS-GEP, 1980). Three separate flow units are exposed on the fault scarp with the Chewkare group of hot springs emerging from the base of the scarp. The Chewkare Ignimbrites are brownish and grayish green, crystal rich ignimbrites locally showing cooling joints and has an exposed thickness of about 100 m. On the road to Abaya Plantation descending the fault scarp the ignimbrites are overlain by the lacustrine sediments (Ql₁) which is intervened by Quaternary basalts. The thickest section of these ignimbrites, out crop along the Northwest Abaya fault scarp which dips about 800 east.

The unit shows a vertical lithologic variation where the base is mainly crystal rich and welded while the top part is pumiceous and poorly welded. Engulfed accidental fragments of basalt (diameter up to few tens of cms) are common near the base. Where some of the tuff bands thicken, a certain degree of fritting has some times taken place at the base, as is typical of ignimbrites. Welding in the tuff is commonly associated with streaks of obsidian or devitrified glass flattened parallel to the bedding.

The ignimbrite at NW Abaya fault is vertically jointed, laterally fissured and fractured with thermal manifestations along the weak zones. Layers of thermally produced clay zones are common. Moderate weathering has changed the original grey colour of the rock to brownish grey colour. A thin section study of the ignimbrite shows fragments of devitrified glass containing spherulites or microlites. Commonly contains crystals of anorthoclase, quartz, scarce amphiboles and pyroxenes. Minor oxidized lithic fragments of basalt /rhyolite are present. Fine vesicular cavities with sporadic infill of calcite are included.
Reported isotopic age for the Chewkare Ignimbrites is 4.4 Ma (EIGS-GEP, 1980) which makes them correlable with Nazret Group Ignimbrites (Tertiary Ignimbrites) in the northern and central MER, where together with the Pliocene Rift floor flood basalts (Bofa Basalts) make the reservoir rock of the Aluto-Langano Geothermal field. Eventhough not widely cropping out in the study area the Bonkoka Basalts are equivalent to the Bofa Basalts.

(c) Damota Trachyte (Ttr2)
Trachytic lava flows from the shield volcanic center of Damota which rises for over 1000 m from the surrounding rift escarpment near Woliata Sodo town. On the steep sided shield of Damota are exposed bare rocks of light greenish gray, porphyritic (with large feldspar phenocryst) trachyte which show cooling joints and more weathering near the flanks of the shield. No definite absolute age determination exists for this center, but it has been generally accepted that it is of Pliocene age and correlable to rift margin centers such as Yerer, Wechecha, Furi in the Addis Ababa area. Damota however shows younger features which suggests that activity might have continued into the Quaternary.

(d) Quaternary Ignimbrites (Qig)
The eastern part of the study area west and southwest of Obicha Caldera is covered by a brown, lithic rich, weakly welded ignimbrite. In river valleys forming tributaries to the Hamesa River (in the vicinity of Humbo town) several tens of meters of this ignimbrite unit are exposed interstratified with Quaternary basalts. The fact that these ignimbrites are exposed in river valleys in an area mantled by Quaternary volcaniclastic sediments indicates that the ignimbrites are older than the lacustrine sediments. Quaternary ignimbrites also crop out on the eastern part of the Kilisa subsheet and are related to earlier caldera forming pyroclastic eruptions from centers such as Obicha and Simbura underlying Abaya rhyolites (Qr1). The beds mapped as Qig in the mapped area are generally not wide spread deposits and not very thick. They out crop at the north -western portion of Tebela sub sheet, at eastern Abaya and also form the edges of river gorges on the floor of Obicha caldera.

They are distinctive owing to the presence of large fragments of obsidian, flattened parallel to the
bedding, sometimes giving the rock an appearance of obsidian agglomerate. Some surfaces show lighter streaks oriented approximately parallel to each other, suggesting fluidity during formation and simulating flow lineation in lava.

A thin section of some of the samples reveals crystals of large phenocrysts of anorthoclase set in a fine matrix of glass shards and pumiceous material. The groundmass has a fluidal texture due to contorted, curved and flattened wisps of clear glass and Y-shaped streaks. A characteristic feature of the rock is the discontinuity of these flattened shards. Scattered fragments of pumice, broken feldspar crystals, basalt, trachyte and rhyolite are the main lithic portions of the ignimbrite though quartz, remnants of olivine grains, amphiboles and pyroxenes were noted in most samples. Rare carbonate veins are present.

(e) Lower Quaternary Pumiceous Pyroclastics (Qp1)

In the mapped area these units are displayed underlying Qr2 at mount Bula area (Tebela sub sheet) and underlying Qr1 at Donga and Metincho area (Kilisa subsheet). Unmapable thin vertical sections also outcrop at various localities including road cut sections at kercheche area (Sodo sub sheet). They are grey and yellowish colored and poorly sorted consisting of accidental fragments (bombs) of rhyolite and basalt. Where sections are available at lower elevations they show some bedding structures, evidencing subaqueous eruptions in the ancestral large lakes of the region, though they often form hilly morphologies that are considered to be islands within the paleo lake basin. These pumiceous pyroclastics belong to the explosive episode of the older rhyolitic volcanic centers.

(f) Abaya Rhyolites (Qr1)

The rhyolites outcrop at the various localities of the mapped region forming older domes. Large volumes of lava and pyroclastic products are exposed on the flanks and caldera rim of Obitcha. A K-Ar age of 1.57 Ma has been reported for a rhyolite flow (Qr1) from the inner caldera wall of Obitcha (EIGS-GEP, 1979) and represents the earliest phase of rhyolitic volcanism in the study area. They are strongly banded in situ with alignment of fine vesicles and brittle thin-banded layers of few cms. Both gray colored and pink colored varieties, weathered to moderate degree are common. Fine grained and moderately porphyritic hand specimens were noted. Other rhyolitic
volcanic centers in the study area include the Simbura (Donga) rhyolitic volcanic complex rises about 1000 m from the Lake Abaya level and is composed of stratified ash and pumice deposits with the base of the volcano being composed of flow banded rhyolite flows ($Q_{r1}$). Stratified pyroclastic layers which gently dip to the northeast, and photo geologic studies indicate a caldera collapse structure with a displacement in excess of 500 mts. The complete circular outline of the collapse structure is marked by smaller rhyolite domes to the southeast which represent resurgent activity after the caldera subsidence of this center getting an appearance of a hinge. Chericha whose near perfect cone rises for about 700 m from the rift floor with a classic summit caldera a few kms in diammter. Other minor rhyolite flows and domes such as at Kilisa (Gedano), Metincho and Bukisa are found all along the axis of the rift.

Petrographically the rhyolites are mildly porphyritic with phenocrysts of anorthoclase, quartz, sodic amphiboles and pyroxene microlites. Orientation of the microlites is common, displaying micro banding structures. Amygdales filled with hematite/limonite are fairly common.

**(g) Lower Quaternary Basalts ($Q_{b1}$)**

The NNE trending fault swarm along the axis of the rift floor has been a conduit for basaltic eruptions with lines of scoria cones making fault traces. These Quaternary basalts in some exposures are interstratified with the earlier succession of the Lake Sediments ($Q_{l1}$).

Eventhough distinguished primarily on the basis of degree of preservation of volcanic structures and intensity of post-emplacement tectonic movements of the flows rather than substantive petrologic or geochronologic evidence two Quaternary basalt members ($Q_{b1}$ and $Q_{b2}$) were mapped. The first pulse of basaltic effusion Tena Bilate Basalts ($Q_{b1}$) is exposed over a broad area between Lake Abaya and Duguna Fango. This unit which is exposed all along the Bilate River bed and banks for most its course in the study area (hence the name Tena Bilate Basalts) with adjoining rift floor being covered by the overlying, intensely denuded lacustrine sediments.

Examination of thin sections of the basalt shows a micro prophyritic texture with small phenocrysts and clusters of plagioclase feldspars and fine-grained olivine. The groundmass consists of lath shaped plagioclase feldspars; fine grained interstitial olivine, iron oxides
(magnetite) and pyroxene microlites. The sub-idiomorphic olivine's are pale brown or nearly colorless and are rarely fresh, showing evidence of resorption and alteration to orange colored iddingsite around the crystal margins. The magnetite forms numerous small octahedral in the groundmass where it is frequently concentrated round the edges of altered olivine's. The vesicular walls are commonly lined with calcite.

**(h)Middle-Upper Quaternary Pumiceous Pyroclastics (QP2)**
These units designated as QP2 in the map extensively out crop at the western, north eastern and eastern flanks of Duguna Fango complex and also on top of the volcano underlying Qr2. The origin of these pumiceous pyroclastics is thought to be intimately associated with the early mountain building explosive activities of the volcano. They have formed hilly morphologies as thick as 500 mts. They are generally fresh and gray and yellowish varieties are common. There are various sizes of the pumice ranging from few millimeters to about 10 cm diameter. Accidental fragments of rhyolite, basalt and ignimbrite are included. The general poor sorting nature indicates deposition not far from the source.

**(i) Duguna Fango Rhyolites (Qr2)**
The rhyolites out crop mainly at Duguna Fango area thus are named Duguna Fango rhyolites. Exposures of the rhyolites are concentrated along the NE - SW trending intensely tectonized strip of land in the central part of the Wonji Fault Belt axis upon which the mountain building activities of Duguna Fango took place.

In this area the rhyolites are considered to have been out poured along ring fractures that have been formed after the initial explosive mountain building activity which laid the pumiceous pyroclastics (Qp2). Exposures of the rhyolite thinly mantle the slopes of the pumiceous piles and information as regards flow directions can be detected from aerial photos. Out crops of the rhyolite also occur at Hako area SW of Duguna Fango. These units have been mapped as Abela Rhyolites by previous surveys (EIGS - GEP 1979).

In hand specimen, they are gray - dark gray colored and commonly are flow banded. Porphyritic varieties with glassy groundmass are abundant. In thin sections, the rhyolites are mildly porphyritic
to coarsely porphyritic with phenocrysts of anorthoclase and minor quartz and sodic amphiboles. The groundmass is finely crystalline with small crystals of feldspars, quartz and intergranular opaque minerals.

**(j) Middle-Upper Quaternary Basalts (Qb2)**

The younger episode of basaltic eruptions outcrops along an axial zone of more recent volcanotectonic activity of the SalwaDore-Hako and northwest Abaya hydrothermal field (Qb2).

In thin sections the basalt samples do not show great variation, but there is a gradation from varieties with micro porphyritic texture to coarsely porphyritic texture. The phenocrysts are plagioclase feldspars and olivine. The groundmass consists lath of fine-grained feldspars, pyroxene microlites and interstitial grains of olivine. The phenocryst feldspars fairly show zonal structure and the olivine is rimmed by magnetite hematite and iddingsite. Some vesicular walls are lined by calcite.

**(k) Recent Rhyo-Obsidian Flows (Qr3)**

They form a composite volcanic cone at mount Seluwa, mantle the south eastern flanks of Duguna Fango volcano and also out crop on top of mount Korke overlying Qr2. The Salwa Dore–Hako rhyolitic center has produced very recent obsidian and pitchstone flows probably representing the youngest rhyolitic activity (Qr3) in the study area. The obsidian lava pile at Seluwa rises sharply to a height of 150 mts from the surrounding plain with small crater on the very top formed by the collapse of the summit (photo no. 1). The base of the mountain is formed by dark gray-greenish colored porphyritic obsidian, the middle part is more greenish and less denser while the top part is highly vesiculated (spongy). There are several fissured flow walls, sub vertically oriented and each sub flow layer has a rugged, fragmented base. The exposure at mount Korke is represented by dense aphyric dark colored obsidian which is dissected by NW-SE trending fissure system. Rhyo-obsidians with porphyritic texture out crop at mount Duguna Fango that were emplaced along ring fractures related to the last episode of tectonism in the area.

Microscopic observation of a sample from mount Seluwa has revealed porphyritic texture with phenocrysts in a decreasing order of abundance, anorthoclase, sodic amphiboles and pyroxenes.
There are small insets of feldspars and acicular pyroxenes in a dominant glassy groundmass. The small crystals are generally aligned representing flow lineation.

**(l) Pleistocene Volcano Sediments (Q1f)**

These are essentially lacustrine sediments of mainly volcanic origin and were related to the existence of large lakes during pliestocene times (Mohr, 1967). They are generally yellowish-grey colored, horizontally beded and poorly sorted with fragments of rhyolite, obsidian and basalt in a matrix of fine tuffaceous ash. Some rounding of the fragments evidenced partial reworking.

The sediments has a wide spread occurrence in the mapped area. As might be expected the pre-sedimentational volcanic surface pen plain was not perfect. Therefore the sediments are missing in some localities that are considered to be residual hills on the peneplain. Younger volcanic products have also covered the sediments in significant proportion of the mapped region. The thickness of the unit is variable depending on the depth of the paleo lake basins in the various localities.

**(m) Holocene Lake Beds (Q12)**

Out crops of these younger lakebeds are limited to localities surrounding Lake Abaya. Lithologically they are mainly constituted by loosely compacted, well sorted, friable and fairly reworked yellowish clay and silt material. Minor carbonates are detected as cementing material. Sub aerially deposited pumiceous materials from the explosive episode of the surrounding volcanic centers are also layered with these sediments.

**(n) Recent Alluvium and Fluvial Deposits (Qal)**

The lower course two major rivers (Bilate and Gidabo) which drain most of the study area into Lake Abaya is covered by fluvial deposits along its gentler course. The flood plain of Bilate River is intensely cultivated using mechanized irrigation by the state farms to grow cotton, tobacco and fruits. Both Bilate and Gidabo Rivers have formed lacustrine deltas on the northern part of Lake Abaya which are a few kilometers wide. Colluvial and outwash debris are found widespread in the study area particularly along foothills of major fault scarps.
Recent deposits in the area include soils and alluvial sand deposits. The soils are mainly residual weathering deposits, whose composition is controlled more by the physical conditions of formation than by the type of rock from which they were derived. On the older basaltic area dark brown cotton soil is common while the soil on top of the ignimbrites is red lateritic.

The alluvial sands include deltaic deposits of Bilate River which occupied the northern shore of Lake Abaya and Gidabo River forms fluvial fans at eastern Abaya. Small tributary rivers of Bilate have also formed fluvial deposits including conglomeratic beds along their gentler slopes.

(ii) Hydrothermal Activity

A variety of active hydrothermal manifestations are found in the Northern Abaya Geothermal Prospect. The distribution of hot springs and fumaroles in the prospect show strong control by tectonic and structural patterns and equally importantly by the hydrogeologic conditions of the area. Most hot springs are found near riverbeds and at the present lake level which suggests the presence of many more sub lacustrine thermal springs. The following areas of active hydrothermal activity and their vicinity were examined:

1. Northwest Abaya Fault hot springs and fumaroles
2. Salwa Dora - Hako fumaroles
3. Hamesa warm springs
4. Donga and East Abaya Fault hot springs
5. Bolocho - Metincho hot springs
6. Bilbo active fumarolic and fossil hotspring areas
7. Tobacco Plantation hot springs
8. Dimtu warm springs

Based on the proximity of the above hydrothermal fields to the Quaternary rhyolitic central volcanic complexes and inferred ground water flow pattern in the region previous studies have suggested that the Northwest Abaya Fault hot springs and fumaroles, Salwa Dora - Hako fumaroles and the Hamesa warm springs are related to the Obicha complex rhyolitic center.
The Donga and East Abaya Fault hot springs related to the Simbura volcanic complex, where as the Bolocho - Metincho hot springs are related to Chericha volcanic center respectively. The Bilbo active fumarolic areas, Tobacco Plantation hot springs and Dimtu warm springs are related to the Duguna Fango volcanic complex (enclosure- to- ).

The surface hydrothermal activity of the area is geographically divided and described as follows:

- (a) Tebela sub sheet (Hamesa, NW Abaya fault and mt. Korke - mt. Seluwa, areas).
- (b) Kilisa sub sheet (mt. Donga and Metincho - Bolocho, areas thermal activities) and
- (c) Chericho subsheet (Tobaco factory, Anka Bilbo and Dimtu, areas thermal activites).

(a) Tebela sub sheet (enclosure- )

**Feature number TE-1A and TE-1B**

Hamesa warm springs are located on the Sodo-Arba Minch road about 10 km south of Humbo town. From near the riverbed and a contact between the Tertiary ignimbrites and the Quaternary Basalt a number of eyes of springs discharge a near neutral water at 30-36°C. Two major springs with moderate low discharge are situated about 100 mts apart from each other. The two features, number TE - 1A and TE - 1B are located bout 300 mts. and 400 mts. SE of the Hamesa River bridge. The southern most spring (TE - 1A) has a temperature of 36°C and spring TE - 1B has a temperature of 34°C. The Lukewarm springs issue from fractures in ignimbrite without any surficially evident alterations.

About a dozen eyes of springs, some forming pools as big as 5 m in diameter discharge around the base of the fault and unstable swampy lake shore of Bora Mita (meaning swallows a bull in the local dialect). Spring #6 (UNDP, 1973) is the hottest (95°C) and most vigorously discharging spring with soft sinter deposit around the vent. This spring was reported to discharge at about 2 m above the lake level, but the vent from where hot water gashes out periodically is nearly submerged by the lake now.
There are local reports that the lake level has risen within the last twenty years which was also confirmed by the invasion of many man made structures by the lake and a swampy ground in the last few decades.

The perched acid spring #7 (UNDP, 1973) at 90°C (Craig, 1977) has been submerged or have had more subsurface influx of cold ground water that it has a lower temperature (40°C) and a near neutral water discharge. However some of the fumaroles on the fault scarp has formed shallow pools filled with acid water condensate but without any appreciable discharge. Some of the fumarolic vents are rimmed with algae overgrowth with sulfur sublimate also common in the surrounding hot ground. A group of springs about 1.5 km north are named as the Chewkare group of springs and emerge from the base of the same fault by the road to Abaya State Farm. Most of these springs have near neutral pH and their temperature ranges between 42°C and 67°C. There is widespread travertine deposit at the base of the fault scarp which indicated profuse hydrothermalism in the past. A more detailed account of the active hydrothermal features in the area is given in the following section:

**Feature number TE – 2:** The most spectacular hydrothermal manifestations in the prospect area are located along the Northwest Abaya Fault in the form of hot springs, fumaroles and hot grounds. The springs and fumaroles emerge from near the base of the western boundary fault of the Cherwkare Graben and discharge at near lake level. Feature number TE-2 is the southern most thermal manifestation along the NW Abaya fault scarp. At the base of the fault scarp that strikes NS and dips about 80°E, thermal springs emanate from fractured ignimbrite unit. The spring outlets have five eyes, the flow rate is high, the measured temperature is 96°C and the pH is 9.4. The springs lie about 1 mt. above the lake level. Bubbling spots are evident at the lake level in the vicinity. An EW trending fissure system runs along the activity up the fault scarp.

About 20m high above the springs and along the fissure system there is a vigorous fumarolic steam vent with a diameter of 2mts and a depth of about 10mts. Sinter has deposited as high as about 15mts above the present hot springs level indicating past higher water levels. Currently sinter is depositing near the discharge points of the springs. The thermal activity has altered the outcropping ignimbrite forming red clay, white clay and patchy yellowish incrustations (sulfur?).
**Feature number TE –3:** About 100m NNW of the fumarolic vent of feature number TE - 3 several spots of bubbling steam condensate pools were observed having a diameter of few cms to few tens of cms(spring # 7,UNDP,1973).

The pools are perched about 50mts high above the present lake level. Fumarolic steam rising from depth, condenses near surface due to partial blockage of the steam path by self sealing clay alterations and the condensate being re heated by the steam underneath forms the bubbling acid pools with PH of 5.6 and temperature of 95°C. Near the present activity, completely sealed past activities has changed to frying pan like surfaces. Alteration of the ignimbrite unit to clay is the dominant alteration type visible at surface. The spot of the hydrothermal activity is located along an E-W trending fissure cross cutting the NW Abaya fault scarp.

**Feature number TE – 4:** It lies about 100mts north of feature number TE - 3. There occur several steaming vents with H2S smell along the slope of the NW Abaya fault and about 50 mts above the lake level. The spot of activity is along a fracture zone formed by NW - SE trending fissure system. The intensity of alteration is high with alteration products of red clay, white clay and yellowish film of incrustations (sulfur?) and measured temperature of 97°C.

**Feature number TE – 5:** A bubbling spring occurs about 400m NNE of feature number TE - 4, very near to the shore of the lake. The spring water gushes out from an EW running fissure system forming a big circular vent of 5mts diameter and about 10mts depth. The spring out let eyes are inaccessible and temperature measurement from the source vent was not possible. Measured temperature about 5mts away from the source vent is 56°C. There are several bubbling springs at the lake surface in the vicinity. About 20 mts. high above the spring level, along the NW Abaya fault scarp, the ground is altered with red clay, white clay and yellowish colored sulfide films. Several weak and deep-rooted fumarolic vents occur at the site. Temperature measurement at the base of the vents was difficult and air cooled temperature of the fumaroles at surficial mouth of the vents is 48°C.
The hydrothermal activity from feature number TE - 2 to feature number TE - 5 forms a strip of altered ground, about 600mts length and 100mts wide along the slope of the NW Abaya fault.

**Feature number TE –6:** It is located about 400mts north of TE -5. Hot springs with about 5 major eyes discharge hot water which overflows in two directions (east and south east) towards the near by gully. The largest spring forms a basin of 6 mts. by 5 mts. dimension and has gas ebullitions which form water domes as high as few cms. The maximum measured temperature is 70°C and the pH is 6.8. The hydrothermal alteration products include, reddish yellow material staining the floor of the spring basin (limonite?) and siliceous and travertine incrustations along the base of the overflow channels. An E-W trending fissure cross- cutting the NW Abaya fault acts as a passage for the hydrothermal fluids.

**Feature number TE – 7:** A hot spring emerges from the base of the NW Abaya fault cross cut by younger EW fissures which is located about 2km NNE of feature number TE -6. The overflow from the spring drains downstream to the east forming hot water basins separated by swamp vegetation. There are moderate gas ebullitions both at the spring outlet and the pools which gives the appearance of boiling but the measured temperature at the spring outlet is only 64°C and the PH is 6.8. The spring has moderate discharge rate. The visible hydrothermal alteration at surface is not significant. Limonitic deposition is evident at the spring source and some old travertine terrace is observed as high as 5 mts. above the present spring level, evidence that water levels were higher in the past.

**Feature number TE – 8:** It is located about 800 mts NE of TE -7. A hot spring from fractures in igmmbrite emerges and flows downstream to the east. It has high flow rate, the measured temperature is 42°C and the pH is 6.9. There are no visible surface alterations.

**Feature number TE – 9:** About 1 km NE of feature number TE - 8 there is a hot spring at the base of the NW Abaya fault which forms an artificial pool with a gravel floored basin (7 mts. X 4.5 mts. and 0.5 mts. deep). The spring has some gas escape and moderate flow rate. The measured temperature is 42°C and the PH is 7.5. An old silica sinter and travertine is exposed as high as 10
mts. above the spring level and laterally extends for about 10 mts., indicating higher water levels and more widespread activity in the past.

**Feature number TE – 10:** In a relatively depressed area on top of mt. Korke rhyolitic volcanic cone, there are weak fumarolic grounds along a NW -SE trending fissure system which cut a very young obsidian flow (Qr3). Four vents with weak steam /gas breath are observed. The maximum measured temperature is 47°C and the hydrothermal alteration is insignificant. Some iron oxides coat the surfaces of the obsidian blocks close to the manifestations.

**Feature number TE – 11:** Weakly pressurized gas issues from the summit of mt. Seluwa which is a steep rising (150 mt above the surrounding plain) obsidian-pitchstone volcanic cone. The gas issues from the surficial mouth of a deep-rooted lava tube of 2 mts diameter on top of the mountain. The temperature is low (33°C) and there are no surficial alterations except some oxide stained products.

**Feature number TE – 12:** About 1 km north of mt Seluwa a weak gassing ground occurs from a vent in a blocky basalt unit (Qb1). The measured temperature is 38°C and there are no visible surficial alterations.

**(b) Kilisa subsheet**
The Donga and East Abaya hot spring are located on the northeastern shores of Lake Abaya. The Donga hot springs emerge from near the base of a rhyolite dome which has been down faulted with an east-west trending fault at its interface with the lake. Three groups of springs with numerous discharge points discharge into the lake and surrounding unstable swampy ground. Overall discharge from these group of springs is substantial and difficult to estimate but has formed a shallow water body with distinctly clear water when compared to the muddy and yellowish color of the main Lake Abaya water. Most discharge points are marked by an algae overgrowth and NaHCO₃ precipitate. Most of the spring waters have a near neutral water (pH – 7.5) and a temperature ranging between 48-52°C. The mapped Springs are numbered as follows:
**Feature number KI - 1 (A, B, C, D):** Four major hot springs lie within an EW stretching land of 2 kms length at the southern flanks of mt. Donga. An EW trending structure acts as a passage for the hydrothermal fluids.

**Feature number KI - 2 (A, B, C, D):** These include Metincho springs located about 6kms SW of Bolocho springs. They are close to the western bank of Bilate River and emerge from fractures in volcano clastic formation mantling a rhyolite dome underneath. The Metincho (meaning salt in the local dialect) are group of hot springs which emerge from a base of a rhyolite dome overlain by a conglomeratic volcanoclastic lacustrine sediments. Discharge from numerous eyes of hot springs join to make a stream. Four major springs (distance between KI - 2A and D is 1 km) are aligned in an EW direction which discharge hot water of maximum temperature 55°C and have a Ph of 7.9. The overflow from the springs forms swampy ground and finally enters the near by Bilate river. Hydrothermal alteration products include clays, yellowish red stained surfaces (limonite?) and thin films of NaHCO3. There is an EW trending fault system that is considered to act as a passage for the geothermal fluids.

**Feature number( KI–3,KI-4,KI-5,KI-6):** These feature numbers represent Bolocho area hot springs which are located a few kilometers west of Chericha volcanic center and a few hundred meters away from Bilate River which flows at the base of Chericha into Lake Abaya. The Bolocho group of springs are a spectacular group of springs which have formed a number of pools which fill depressions on top of sinter and travertine cones which are up to about 10 m high from the surrounding plain with a base diameter of up to 200 m. The sinter and travertine cones are formed by precipitation during an overflow from the pools, and indicates that the group of springs were discharging much more vigorously in the past.

**Feature No.KI-3.** This feature number designates one of the hot spring activity at Bolocho area (close to Bilate military camp and about 1 km east of Bilate River course) that has formed a sinter cone of 10 mts height and 200m radius. The white colored, fissile and thinly layered extensive silica sinter evidences a more vigorous activity in the past. A pool formed by its discharge swallows the spring eyes. Measured temperature in the pool is 70°C and the PH is 7.9
**Feature number KI – 4:** About 100 mts NW of feature number KI - 3 lies a sinter cone of 5 m height and 100m radius. A spring with low discharge rate, temperature of 74°C and Ph of 7.8 occurs on top of the cone.

**Feature number KI – 5:** It is located about 100mts NNE of feature number KI - 4. Inside the base of a sinter cone of 3mts height and 10mts radius a spring discharges hot water of 91°C with PH of 7.8. The discharge rate is high and the water is nearly boiling with gas evolutions. Both white and red brown siliceous layers have formed from the spring precipitates.

**Feature number KI – 6:** A sinter cone of 3mts height and 50mts radius lies 100mts east of feature number KI - 4. The spring activity, which formed the cone, is currently dormant.

**(c ) Cherico sub sheet**

The hydrothermal activities in this sub sheet include the tobacco plantation hot springs, the Bilbo active fumarolic and fossil hot springs and the Dimtu warm springs.

The tobacco plantation hot springs emerge from within a vesicular basalt flow unit (Qb₁) which makes the Bilate River bed in the area. Numerous discharge point were identified on a site east of the river with some forming pools and a large discharge which forms a stream which joins Bilate River at a temperature of about 45°C. Temperature of these group springs at the discharge point ranges between 50°C and 61°C with a near neutral pH. About 2 km downstream from these group of springs on the Bilate River banks are located other group of springs with much smaller discharge but higher temperature (67°C to 72°C) and a pH of 7.5. The latter group of springs were being pumped to the tobacco processing plant in the past as was evident from an abandoned pump site. A thin crust of bicarbonate salt in the vicinity of the springs represents the only type of hydrothermal alteration and mineralization at these features. The detailed survey of the alterations at the tobacco monopoly area has identified the following hydrothermal features:

**Feature number CH – 1:** About 1km SSE of the tobacco factory, along the right bank of Bilate River, sets of small springs and seeps emerge up to 0.25mts above the river, from fluvalatile sandy sediments. The visible discharge is low and their temperature ranges from 67°C to 72°C.
Feature number CH- 2: Located 100mts NW of CH - 1 at the foot of a blocky basaltic exposure (Qb1) on top of the sediments. A spring emerges with moderate flow rate, temperature of 64°C and pH of 7.5.

Feature number CH – 3: 1.5 kms SE of the tobacco factory, a spring with several eyes emerge, which flow to an artificial pond. The hot water in the pond is being pumped for the factory employees domestic use purposes. The total flow rate is moderate, the temperature is 51°C and the pH is 7.3. The spring emerges from basalt - sediment interstratified layer and there is thin silica / travertine incrustations layer on the surfaces of the basaltic blocks. Red yellowish colored limonite(?) coating prevail close to the discharge points.

Feature number CH – 4: Two sets of springs occur 600mts SE of the tobacco factory, which emerge from basalt - sediment contact zone and are, separated by few tens of mts. The northern spring has moderate flow rate, temperature of 57°C and PH of 7.3. Thin white bicarbonate incrustations and limonitic alterations are evident at the spring mouth. Immediately south emerging from a basaltic tongue overlying the sediments, there is another spring with moderate flow rate, temperature of 59°C and Ph of 7.2. Minor alterations have deposited limonite around the mouth of the spring.

Feature number CH - 5 and CH – 6: These springs with temperature of 51°C and PH of 7.4 are located about 1 km east of the tobacco factory. They emerge from a basalt - sediment contact zone and their over flow drain SE towards Bilate River as hot water stream. The springs are aligned NS, separated by 300mts and the northern spring is designated CH - 6. Their discharge rate is moderate and no visible alternations prevail at surface.

Bilbo active fumarolic and fossil hotspring areas are located on the southern flanks of the Duguna Fango volcanic complex close to the Bedesa - Dimtu road. The Anka Bilbo fumaroles are situated along the Wadu stream, where hot ground and weak fumarolic vents are found in a country rock consisting of rhyolitic glass. No hissing sound can be heard around the fumarolic vents and a temperature as high as 89°C was measured at some of the vents. Hydrothermal alteration is spread
out over an oval shaped tract of land with about 600 m diameter and appears to be deep rooted. The products of hydrothermal alteration are predominantly brick red clay and yellowish kaolinitic clay with disseminated sublimates of sulfur.

A few kilometers due south from the Anka Bilbo fumarolic site are found the Horea Bilbo fumarolic and fossil hot spring sites where several fumarolic vents with a strong hissing sound are located on a N-S trending fault scarp formed on a flow banded rhyolite. Three major (high pressure) and a few minor vents are found on the scarp and temperatures measured range between 95°C and 97°C. Some of the lower temperature vents spit out condensates with no appreciable outflow from the small and shallow pools formed. Hydrothermal alteration along the fault scarp is in the form of brick-red and the yellowish clay minerals around the vents and minor travertine and sinter deposition which indicated that those vents used to be sites of nearly boiling alkaline chloride springs.

A few hundred meters down slope from this major fumarolic vents in a dry stream bed are found weaker fumarolic vents. The fumarolic acid alteration along this river bed is overlain by about 20 cm thick travertine deposit which also indicated a profuse hot spring activity in the past. The detailed survey has numbered and further described the Anka Bilbo area thermal activities.

**Feature number CH – 7:** Four kms south of the southern base of mt. Duguna Fango at a locality named Beleka moderately active steaming grounds occur along the western slope of a NE - SW elongated scoraceous ridge. Several steam vents issue steam with temperature of 57°C. The scoraceous basalt is partly altered to red clay. Spots of globular siliceous depositions are also evident. The passage for the thermal activity seems to have been controlled by NE- SW trending structure, which dissects the western base of the ridge.

**Feature number CH – 8:** Fumaroles are emanating from the western base of a rhyolite dome locally known as Aba Gutu dome, about 1.5 kms NW of CH -7. The site of the thermal activity lies along a NE - SW trending structure at the base of the dome. The fumaroles have about four vents separated by few tens of meters. The activity is vigorous and has a hissing sound.
measured temperature is $97^\circ C$ and the total altered area is about $1000m^2$). The hydrothermal alteration products include red clay, white clay and sulfides.

**Feature number CH – 9:** About 400 mts NW of CH-8 on the floor of a gully occupied by seasonal stream (Wadu stream) fumarolic gas bubblings occur in small ponds with temperature of $93^\circ C$. The pools are acidic with PH of 6. A tract of rhyolite exposure along the gully is altered to red clay.

**Feature number CH – 10:** At the southern flanks of mt. Duguna Fango complex (locality name Fango Bijo), there is an extensively altered rhyolite exposure. The hydrothermaly-altered tract of land is elongated in a NE - SW direction along a fault structure and covers an area of about 30,000 m$^2$. The temperature of the fumaroles range from 88$^\circ C$ to 95$^\circ C$, the maximum being towards the southern portion, at lower elevation, where higher water table made the activity more vigorous. The products of alteration include red clay and white clay. Some silica-hardened surfaces are also observed, evidence that an old hot spring activity was in place.

The Dimtu warm springs consist of numerous large discharge warm springs with temperature ranging between $38^\circ C$ and $40^\circ C$ and a near neutral pH. The springs emerge from the sand bedded gullies (up to 5 m deep) formed within the lake sediments, to collectively form a stream which drains into Bilate River. Hydrothermal alteration is minor and is represented by a thin film bicarbonate salts on the lacustrine sediments. These springs are numbered and further described as follows:

**Feature numbers CH-11, CH-12 and CH-13:** They lie from 100m to 300m north of Dimtu village and 300m east of Bilate river course and emerge from the base of gullies cut in fluvatile sediments. Luke warm water oozes from conglomeratic beds at the base of the gullies and forms small hot water streams draining to Bilate River. CH-12 has a temperature of $35^\circ C$ and PH of 7.6, CH-13 has a temperature of $37^\circ C$ and PH of 7.6 and CH-11 discharges a hot water of $400^\circ C$ with PH of 6.9. Rust like deposit coats the conglomerate bed where the Luke warm water seeps in.

Other forms of hydrothermal manifestations are found in the vicinity of the mapped area north and northwest of the Duguna Fango volcanic complex. These hydrothermal manifestations include the
warm springs along the banks of the river Chereka and its tributary Busha represent a high discharge low temperature hot spring activity (32-35°C) related to Duguna Fango. The Boroa springs about 10 km NE of Duguna emerge from within a vesicular basalt unit and some form pools as big as 3 m in diameter and about 30 cm deep which drain into the swampy ground which makes the flood plain of Bilate River. Numerous discharge points exist in this locality with all the springs collectively forming a stream which drains into Bilate. The Boroa springs discharge water at a temperature between 43-45°C with near neutral pH.

Most hydrothermal alterations in the study area are found along the lines of tectonic movements of the WFB and are related to the axial volcanic centers. Hydrothermal alteration is found over a wider area around the active hydrothermal manifestations, which indicates that the circulation of hydrothermal fluids had decreased in most cases in response to the dropping down of the regional peziometric level and the self sealing of the hot water aquifers. The hydrothermal alteration in the study area can be grouped into three major types:

- Alterations related to active fumarolic vents, which is commonly deep rooted and pervasively affects the country rock with a wide spread exposed surfaces of kaolinized country rock and native mineral sublimates such as sulfur.
- Alteration related to hot spring activity is commonly represented as superficial deposition of travertine and siliceous sinter, except when the springs are steam heated and related to fumarolic activity in the vicinity.
- Hot grounds, which are, for the most part heated by conduction, form wide areas covered with a thin film of bicarbonate salts indicating subsurface boiling.

2.1.4 SUMMARY OF THE RESULTS

As far as the age of the hydrothermal system in the Abaya Geothermal Prospect is concerned, no quantitative data are yet available. However, it has been established that in all areas of the study the host rocks are ignimbrites and rhyolite lavas with subordinate basaltic rocks. Thus, the hydrothermal activity is mostly hosted in acidic rocks emitted from central volcanoes during late
quaternary times. Hence, all geothermal manifestations are associated with the Quaternary to Recent volcanic centers and are found along lines of tectonic movements of the WFB.

In general, the hydrothermal activities in the study area in a decreasing order of intensity are: the NW - Abaya fault area, the Anka Bilbo area, the Tobacco factory area, the Metincho - Bolocho area, the Donga area, the Dimtu area, the Amesa area and Mt. Korke and Mt. Seluwa area.

The NW Abaya fault area and the Amesa area hydrothermal activities apparently have their heat source from Obicha rhyolitic center. The weak gassing vents at Mt. Korke and Mt. Seluwa are most likely related to conducted heat from underneath the volcanics. The Donga area thermal springs are related to the holistic volcanic of Mt.Donga itself. Chericha rhyolitic volcanic center, which lies adjacent to Bilate River, is the probable heat source of the Metincho-Bolocho area and the Tobacco factory area hydrothermal activities. The Anka Bilbo area and Dimtu area hydrothermal activities being closer to the Duguna Fango complex have their heat source from there.

The thermal springs are all located closer to surface water bodies such as Lake Abaya and Bilate River, due to higher pizeometric levels. The NW - Abaya fault springs and the Tobacco factory springs are the most important one. The extensive hydrothermal activity is controlled by NE - SW trending normal faults in some cases cross cut by open fissures. The hydrothermal alteration related to the thermal springs consists deposition of travertine and silica sinter. Some of the springs evolve CO2, which increases the pH near the surface and results in limonite deposition.

Evidence of an old travertine deposit and silica sinter at the NW Abaya fault springs, particularly in the north, suggests that its activity was once extensive and vigorous. The apparent decrease in activity may have resulted from calcite / silica blockage of feeding fissures near the surface. The high CO2 discharge in some of the springs suggests high CO2 concentrations. Hence, calcite will tend to deposit as steam is separated from the ascending water column. The present lowering of the pizeometric levels also contributed to reductions in the extent of the spring's activity. Comparison of the present measured temperature values with that of UNDP (1973) indicate a general increment of temperature(heating).
In the areas of low pizeometric levels the hydrothermal activity consists mainly of steaming grounds. The fumarolic activity in the Anka Bilbo area, which is related to the Duguna Fango complex, is the most intensive one. In fact, the most interesting feature of this area is the extensive hydrothermal activity, which is controlled by NE - SW trending normal faults. Steam heated acid sulfate alterations are indicated by advanced argillic alterations which are limited to areas in proximity to the vents. Red clay, sulfur, crust form quartz and granular silica are included alteration products. Weakly developed surface alteration zones locally occur in Mt. Korke and Mt Seluwa area. The only apparent alterations are Fe and Ti oxides.

The overall characteristics and distribution of the hydrothermal activity, is related to the different rhyolite central volcanoes, suggest the existence of several systems within the prospect area, even though it needs to be confirmed by integrated geological, structural, fluid-geochemical and geophysical data. Moreover, the geological, tectonic and hydrothermal phenomena investigated indicates the presence of high enthalpy geothermal system. The near boiling Na-Cl type spring discharge in the NW-Abya fault area, the extensive areas of kaolinization related to the Anka Bilbo fumarolic area and the high temperature springs of Tobaco factory area, all attest to the presence of such a resource.

According to available fluid geochemical studies in the northern Lake Abaya geothermal prospect, the NW Lake Abaya hydrothermal field shows the existence of a high temperature hydrothermal system. Hydrothermal alteration deposits suggest a more vigorous hydrothermal activity in the past. Even though the proposed heat source (Obicha or SalwaDore - Hako) for this hydrothermal field is tens of kilometers to the north the intensity and type of hydrothermal alteration supports that the area be investigated in more detail.

The nature of hydrothermal alteration in the Bilbo and Bolocho areas also suggests the subsurface circulation of high enthalpy hydrothermal fluids from most probably different hydrothermal systems. The Bilbo area related to the Duguna central volcanic complex and the Bolocho area
related to the Chericha central volcanic complex are therefore considered to be of second and third priority for a more detailed geoscientific study.

2.2 GEOCHEMICAL EXPLORATION

2.2.1 INTRODUCTION

The main objective of this work is to determine deep temperature and to identify the water type of the hot, and warm springs as well as surface features in the Abaya geothermal prospect (Figure 25). The hot springs are described from north to south. Their locations are shown in figure 26, and are marked with numbers together with a prefix, SP, which stands for spring.

For the purpose of the study, 15 springs out of which 5 are warm, having temperatures between 34 and 58°C: Humesa (SP-1), Chawokare (SP-2), Boramita (SP-3), Dimtu (SP-7) and Bilbo (SP-8), have medium to high flow rate. The other 9 springs are hot, having temperatures between 67-95°C and with an appreciable flow rate and one cold spring with a temperature of 19.2°C having variable flow rate, that is high during rainy season and low during dry season. The other features sampled are surface waters from Lake Abaya and from rivers (Bilate, Humesa and Bedesa).

2.2.2 MATERIALS AND METHODS USED

a) Field work

Water samples were collected from hot, warm and cold springs with high temperature and having high flow rate. Lake water sample was collected at about 20 meters distance from the lakeshore and by deepening the sample vessel to a depth of about 0.5-meter. River water samples were collected from the central portion of the channel and are supposed to reflect the cumulative flow from several tributaries and seepage from groundwater.

Water samples collected for SO₄ and Cl⁻ and for cation analyses were filtered and treated using ZnAc (zinc acetate) and hydrochloric acid having a one to one concentration respectively in situ. Filtration was done using a hand pump-filtering device, which operates manually through 0.45μm filter paper. The filtered and treated samples were stored in 125ml polyethylene plastic bottles. The purpose of acidification is to let the metals remain in solution.
For SiO₂ (silica) determination 20ml of sample was taken and was diluted to a volume of 100ml with distilled water in order to avoid polymerization that may occur between the period of sampling and analysis.

Untreated and unfiltered samples were collected and stored in 500-ml polythene bottles for anion determination. 50ml samples were collected for ¹⁸O and ²H (oxygen-18 and deuterium) isotope determination. 500 ml of sample was collected for ³H (tritium) unit counting. All polyethylene bottles have double capes with airtight seal.

Other than the treating and filtering processes pH, temperature, Eh, TDS, SiO₂ and Electrical conductivity and latitude and longitude coordinates have been measured and recorded accordingly at each sampling point in the field and the results are given in table 11.

Table 11. Field analysis results of water samples from the Abaya Geothermal Prospect.

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<th>Date of Sampling</th>
<th>Coordinate</th>
<th>Feature Name</th>
<th>Feature Location</th>
<th>Conductivity µS/cm/°C</th>
<th>TDS mg/l/°C</th>
<th>sample °C</th>
<th>pH units/°C</th>
<th>Eh mv/°C</th>
<th>SiO₂ ppm</th>
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<td>W.spring</td>
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<td>166/34</td>
<td>35</td>
<td>6.7/34</td>
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<td>H. spring</td>
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<td>5 23 7N</td>
<td>Gola</td>
<td>C.spring</td>
<td>54/19</td>
<td>25/19</td>
<td>20</td>
<td>5.6/19</td>
<td>81/19</td>
<td>38</td>
</tr>
<tr>
<td>07/5/2000</td>
<td>6 42 01N</td>
<td>R.H. Humbo</td>
<td>Rain</td>
<td>17</td>
<td>18</td>
<td>17</td>
<td>6.2/17</td>
<td>79/17</td>
<td>17</td>
</tr>
<tr>
<td>08/5/2000</td>
<td>6 34 10N</td>
<td>Humesa</td>
<td>River</td>
<td>42/23</td>
<td>20/24</td>
<td>24</td>
<td>7.9/24</td>
<td>46/24</td>
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<tr>
<td>14/5/2000</td>
<td>6 40 08N</td>
<td>Bl.R. Bilate</td>
<td>River</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>7.9/24</td>
<td>46/24</td>
<td>130</td>
</tr>
</tbody>
</table>
b) Laboratory

The GSE laboratory analyzed the chemical concentration of the samples and results are shown in Table 12.

Samples for isotope analyses such as deuterium ($^2$H), oxygen-18 ($^{18}$O) and for tritium ($^3$H) unit counting were collected and they are sent to the I.A.E.A. (International Atomic Energy Agency) Isotope Hydrology Section cited in Vienna-Austria.

The reliability of chemical analysis of water samples was determined using the analytical deviation method and the results were found to fulfill the $-5\%$ and $+5\%$ analytical error which suggest that the analytical results are reliable for further Geochemical interpretation.

Table 12. Chemical analysis results of the water samples from the Abaya geothermal Prospect (Constituents in mg/l or ppm).

<table>
<thead>
<tr>
<th>Feature name</th>
<th>Feature Code</th>
<th>pH</th>
<th>Conductivity µS/cm/25ºC</th>
<th>Na</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>CO$_3$</th>
<th>HCO$_3$</th>
<th>Cl</th>
<th>SO$_4$</th>
<th>NO$_3$</th>
<th>F</th>
<th>SiO$_2$</th>
<th>B</th>
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<tbody>
<tr>
<td>Humesa</td>
<td>Sp-1</td>
<td>7.40</td>
<td>380</td>
<td>49</td>
<td>9.3</td>
<td>20</td>
<td>7</td>
<td>239</td>
<td>8</td>
<td>&lt;0.4</td>
<td>1.77</td>
<td>1.55</td>
<td>144</td>
<td>0.17</td>
<td></td>
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<td>Chawokare</td>
<td>Sp-2</td>
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<td>1416</td>
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<td>34</td>
<td>40</td>
<td>775</td>
<td>104</td>
<td>22</td>
<td>0.89</td>
<td>2.71</td>
<td>107</td>
<td>0.03</td>
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<tr>
<td>Boramita</td>
<td>Sp-3</td>
<td>7.59</td>
<td>1560</td>
<td>213</td>
<td>26</td>
<td>53</td>
<td>56</td>
<td>887</td>
<td>103</td>
<td>24</td>
<td>0.89</td>
<td>2.78</td>
<td>123</td>
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<td></td>
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<tr>
<td>Boramita</td>
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<td>5628</td>
<td>1370</td>
<td>174</td>
<td>0.2</td>
<td>&lt;0.1</td>
<td>596</td>
<td>1069</td>
<td>89</td>
<td>1.3</td>
<td>46</td>
<td>433</td>
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<td>Sp-6</td>
<td>7.68</td>
<td>2147</td>
<td>510</td>
<td>32</td>
<td>19</td>
<td>9</td>
<td>1378</td>
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<td>14</td>
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<td>Bilbo</td>
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<td>7.66</td>
<td>906</td>
<td>192</td>
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<td>12.8</td>
<td>3</td>
<td>514</td>
<td>55</td>
<td>23</td>
<td>3.1</td>
<td>15</td>
<td>118</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Dimtu</td>
<td>Sp-8</td>
<td>7.94</td>
<td>950</td>
<td>202</td>
<td>16</td>
<td>12</td>
<td>2.8</td>
<td>540</td>
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<td>1212</td>
<td>292</td>
<td>16</td>
<td>6.5</td>
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<td>675</td>
<td>51</td>
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<td>&lt;0.03</td>
<td>20</td>
<td>150</td>
<td>0.25</td>
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<td>Bilate</td>
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<td>8.12</td>
<td>1212</td>
<td>292</td>
<td>16</td>
<td>6.8</td>
<td>1.9</td>
<td>687</td>
<td>55</td>
<td>12</td>
<td>&lt;0.03</td>
<td>20</td>
<td>134</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Bilate</td>
<td>Sp-11</td>
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<td>1218</td>
<td>280</td>
<td>13.1</td>
<td>6.4</td>
<td>1.5</td>
<td>677</td>
<td>50</td>
<td>10</td>
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<td>20</td>
<td>128</td>
<td>0.03</td>
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<tr>
<td>Bilate</td>
<td>Sp-12</td>
<td>8.00</td>
<td>1058</td>
<td>238</td>
<td>18.7</td>
<td>15.6</td>
<td>2.4</td>
<td>595</td>
<td>56</td>
<td>30</td>
<td>&lt;0.03</td>
<td>15</td>
<td>118</td>
<td>0.12</td>
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<tr>
<td>Metincho</td>
<td>Sp-13</td>
<td>8.33</td>
<td>1483</td>
<td>342</td>
<td>18.1</td>
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<td>2</td>
<td>827</td>
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<td>144</td>
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<td>Sp-14</td>
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<td>4382</td>
<td>1270</td>
<td>66</td>
<td>1.1</td>
<td>0.1</td>
<td>1</td>
<td>2830</td>
<td>126</td>
<td>64</td>
<td>&lt;0.03</td>
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<td>251</td>
<td>1.11</td>
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<tr>
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<td>Sp-15</td>
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<td>3</td>
<td>1.3</td>
<td>0.3</td>
<td>15</td>
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<td>&lt;0.4</td>
<td>8.86</td>
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<td>Abaya L.</td>
<td>A.L.</td>
<td>8.76</td>
<td>990</td>
<td>206</td>
<td>14.5</td>
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<td>4.3</td>
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<td>477</td>
<td>60</td>
<td>15</td>
<td>0.44</td>
<td>7.39</td>
<td>19</td>
<td>0.24</td>
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<td>Humesa R</td>
<td>H.R.</td>
<td>6.74</td>
<td>84</td>
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<td>10.1</td>
<td>2.7</td>
<td>51</td>
<td>4</td>
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<td>0.52</td>
<td>24</td>
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<td>Bedesa R.</td>
<td>B.R.</td>
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<td>150</td>
<td>24.2</td>
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<td>0.9</td>
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<td>1.4</td>
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<tr>
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</tbody>
</table>

2.2.3 INTERPRETAION OF THE GEOCHEMICAL RESULT

The ternary diagram, which is mostly applied to geothermal waters, has been used for the classification of the waters collected from the study area. The percentage content of Cl, SO₄ and HCO₃ are used in plotting the ternary diagram, (Fig 26). In here, compositional ranges are indicated for typical groups of thermal waters such as volcanic and steam heated formed by the adsorption of high temperature.

Because of the above analysis, three types of water are identified using the triangular method, based on their percentage concentration of chloride. Most of the waters are bicarbonate type with about 10% of chloride. One cold spring has chloride content of about 25% and the third one is Wache hot spring having 45% of chloride content. Therefore, the three water types identified are:

1) HCO₃ type with 10% of Cl
2) HCO₃ type with 25% of Cl
3) HCO₃ type with 45% of Cl

Springs: SP-1, SP-7 and SP-8 all has low chloride, 8-72 ppm with the exception of SP-2 and SP-3 have chloride values of 104 and 103 ppm respectively. Cl/total bicarbonate ratio of these springs is
(0.03–3.67). Their conductivity values range between 352 and 1387 µS/cm/25ºC, and they have TDS values that range from 166 - 669 mg/kg at different temperatures. Humasa spring has the lowest cation and anion content than the Chawokare and Boramita springs, but it has relatively higher SiO₂ (silica) content than both. They have pH values near neutral to slightly alkaline (Table 12).

The warm springs mentioned above have relatively higher Ca and Mg content than the hot springs which might indicate that they are of shallow source heated by steam injection into ground waters. There is no evidence from the chemistry that high temperatures exist under any of these springs.

(ii): Molecular ratio of water samples

Wache is however near boiling (95ºC), deposits some siliceous sinter. Has high discharge and high Cl value 762 ppm and highest Cl/SO₄, Cl/total bicarbonate and Cl/F ratios in the area under study. It has also low Ca and Mg and high Na/K ratio, which might suggest high underground temperature. There are qualitative and quantitative geothermometers. Thus high Na/Ca, Na/Mg and Cl/F ratios may generally be used as qualitative indicators of high underground temperatures. Since, Wache (SP-5) and Bolocho (SP-14) show high Na/Ca ratio (Table 3), these might indicate high, underneath temperature.

Soluble constituents in association with chloride may be used to determine whether the system contains one or several hot water aquifer. According to the Cl/B ratio (Table 13), SP-3, SP-4, SP-6, SP-7 and SP-12 may be classified into one group. Wache, SP-5 is different and cannot be grouped with others. SP-11, SP-10 and SP-2 are grouped together. In steam heated waters the Cl/SO₄ ratio is relatively low due to oxidation of H₂S transported in the steam phase.

The Na/K ratios for the hot springs are low and for the warm springs are relatively high which might indicate high temperature for the hot springs and vice-versa for the warm springs. The similarity of Cl/B ratio for the first group indicates that the waters originate from one aquifer with similar rock environment. However, the Cl/B ratio of the second group is low than the other two groups and this might be due to two reasons (UNDP, 1973):

1) If the waters migrate through sedimentary rock which are usually high in boron.

2) In steam heated water boron is slightly soluble as boric acid in the steam phase.
Table 13. Molecular ratios of Water Samples from the Abaya Geothermal Prospect

<table>
<thead>
<tr>
<th>feature</th>
<th>Na/K</th>
<th>Na/Ca</th>
<th>Na/Cl</th>
<th>Cl/HCO3</th>
<th>Cl/F</th>
<th>Cl/SO4</th>
<th>B</th>
<th>Cl/B</th>
<th>SiO2/Cl</th>
</tr>
</thead>
<tbody>
<tr>
<td>sp-1</td>
<td>5.27</td>
<td>2.45</td>
<td>6.13</td>
<td>0.03</td>
<td>5.16</td>
<td>2.00</td>
<td>0.18</td>
<td>43.26</td>
<td>18.00</td>
</tr>
<tr>
<td>sp-2</td>
<td>8.58</td>
<td>6.56</td>
<td>2.14</td>
<td>0.13</td>
<td>38.38</td>
<td>4.73</td>
<td>0.04</td>
<td>2811.85</td>
<td>1.03</td>
</tr>
<tr>
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<td>8.19</td>
<td>4.02</td>
<td>2.07</td>
<td>0.12</td>
<td>37.05</td>
<td>4.29</td>
<td>0.22</td>
<td>469.35</td>
<td>1.19</td>
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<td>12.93</td>
<td>33.13</td>
<td>7.36</td>
<td>0.05</td>
<td>4.80</td>
<td>5.54</td>
<td>0.24</td>
<td>301.03</td>
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</tr>
<tr>
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<td>8.56</td>
<td>3.13</td>
<td>243.33</td>
<td>0.57</td>
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<td>26.84</td>
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<td>4.69</td>
<td>0.11</td>
<td>549.75</td>
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<td>0.11</td>
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<td>2.39</td>
<td>0.17</td>
<td>332.92</td>
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</tr>
<tr>
<td>sp-8</td>
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<td>0.04</td>
<td>1.53</td>
<td>1.05</td>
<td>2.19</td>
<td>10.49</td>
<td>5.83</td>
</tr>
<tr>
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<td>5.00</td>
<td>0.04</td>
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<td>0.44</td>
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<td>103.86</td>
<td>1.99</td>
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<td>0.33</td>
<td>50.00</td>
<td>12.50</td>
<td>0.18</td>
<td>27.04</td>
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<td>0.08</td>
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<td>40.00</td>
<td>0.20</td>
<td>19.78</td>
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<td>12.10</td>
<td>4.03</td>
<td>0.07</td>
<td>4.29</td>
<td>15.00</td>
<td>0.04</td>
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<td>0.11</td>
<td>6.53</td>
<td>32.50</td>
<td>0.15</td>
<td>87.87</td>
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</tbody>
</table>

The Hot Springs: Wache (SP-5), Bolocho (SP-14), and Bilate (SP-10) have temperatures 95, 89, and 71°C respectively, and high conductivity value 5628µs/cm/25°C, which is about four, times that of Bilate. Wache has TDS value of 2860 mg/kg and Bolocho has 2230 mg/kg, but Bilate has four times lesser value. Both Bolocho and Bilate have pH values near neutral to slightly alkaline but Wache hot spring has a high pH value 9.61 which is alkaline. It has CO3 (carbonate) content of 596 ppm while the other two springs have none. Wache and Bolocho hot springs have high Na and K content but they have low Ca and Mg values. Mg concentrations in geothermal fluids rapidly decrease as the temperature increases, (Fournier 1988), and this in turn might indicate that Wache and Bolocho have come from a deep reservoir of higher temperature.
iii) Chemical geothermometers: One of the most useful parameters to know in the assessment of thermal systems for practical use is the actual temperature of the main geothermal reservoir. For doing so, the application of solute chemical geothermometers is inevitably very essential. Qualitative geothermometers especially the cation geothermometers are widely used to calculate subsurface temperatures of waters collected from hot springs and wells (Giggenbach 1988). Currently there are different geothermometers suggested by different authors (Table: 4). It is rare that they all give the same result especially when applied to hot springs.

When Silica precipitation occurs in the up flowing zone and when waters have appreciable concentration of Ca, the Na-K-Ca geothermometer may give more reliable results than the SiO₂ and Na/K geothermometer.

\[
\text{Na-K-Ca } T^\circ C = \left(1647/\log (\text{Na/K}) + \beta (\log \sqrt{\text{Ca/Na}}) + 2.06\right) + 2.47 - 273.15
\]
Where $\beta$ is $1/3$ for waters equilibrating above $100^\circ C$ and $\beta$ is $4/3$ for waters equilibrating below $100^\circ C$. An exception to the above rule is that $\beta$ equal to $1/3$ should be used for waters less than $100^\circ C$ when $\log(\sqrt{\text{Ca}/\text{Na}})$ is negative. All concentrations are expressed in milligrams per liter or parts per million (ppm).
Table 4: Temperatures calculated using different geothermometers

<table>
<thead>
<tr>
<th>Feature Name</th>
<th>feature Code</th>
<th>T°C-1</th>
<th>T°C-2</th>
<th>T°C-3</th>
<th>T°C-4</th>
<th>Na-K-Ca T°C</th>
<th>K-Ca T°C</th>
<th>K-Mg T°C</th>
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<td>159</td>
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*(iv) Na-K-Mg diagram*

Of all other geothermometers given in table: 14, the Na-K-Ca and the Na/1000-K/100-√Mg geothermometer shown in the ternary diagram (Fig: 26), which is plotted using the percentage concentration of Na/1000-K/100-√Mg are found to be reliable. They have given very reasonable underneath temperatures. Therefore, from the above geothermometry analysis it was found that Wache hot spring to be the most promising one in the study area, followed by Bolocho.

From the ternary diagram given in (Fig. 26), it is possible to see that both Wache and Bolocho waters are in the full equilibrium region with reservoir rock temperature at about 260 and 180°C respectively. The other samples are plotted in the immature zone, suggesting low subsurface temperature.
2.2.3 SUMMARY OF THE RESULTS

As a result of the above Geochemical study, the following conclusions are made about the Abaya Geothermal prospect:

1) The apparent decrease in the activity of the springs may have resulted from scaling blockage of feeding fissures near the surface and this may inhibit the flow of deep chloride water to the surface. This might be the reason why the flow rate has significantly decreased while the temperature has almost remained the same since the UNDP study of 1973.

2) Using the cation geothermometers suggested by different authors and making use of the Na/1000-K/100-√Mg ternary diagram given by Giggenbach, (1988) Wache, (SP-5) was found to be in full equilibrium with the reservoir rock at a temperature of about 260°C and Bolocho, (SP-14) of 190°C. The Na-K-Ca geothermometer has also given similar subsurface temperature of 273 and 194°C to that of Wache and Bolocho respectively.

Future studies such as geophysical investigation and drilling of temperature gradient wells are recommended to focus on Wache area with first priority to be followed by Bolocho.

2.3 GEOPHYSICAL EXPLORATION

2.3.1 OBJECTIVE OF THE GEOPHYSICAL WORK

In an attempt to promote the knowledge of subsurface geological and tectonic features in the study area; and locate and delineate potential (prospective) zones of geothermal resource, an integrated geophysical survey was conducted in the Duguna Fango volcanic area, Anka Duguna, the Tobacco plantation, Dimtu and the localities west of the Bilate River (Fig. 27).

2.3.2 METHODOLOGY

(i) Survey Layout

Since part of the survey area was a rugged topography with thick vegetation cover, the volume of topographic line cutting and detail electrical resistivity coverage was only limited to the relatively flat topography. Hence, most semi-regional geophysical surveys were conducted mainly along
secondary roads and accessible routes. Detail electrical resistivity surveys were carried out only along topographically surveyed lines. Although, the need of additional and extension survey lines was felt, time and budget constraints prohibited this plan to be accomplished. Two potential field methods, gravity and magnetics were carried out along semi-regional traverse lines at a station interval of 1-2 km. In addition, a relatively detailed data acquisition was conducted along topographically surveyed lines every 500 m (Fig. 27). These traverse lines include: Bedessa-Fango-Dimtu, Bedessa-Anka-Bilate, Dimtu-Cericho and Anka village-Anka Fumaroles. The detail geophysical survey lines are shown in Fig. 2 (profiles 1-6). A total of 138-line km of gravity and magnetic data acquisition was carried out.
(ii) Geophysical Methods

(a) Electrical Resistivity Survey

Electrical resistivity survey was conducted along profiles 1-4 and profile 6. The survey consists of Vertical Electrical Sounding (VES) observations and profiling at an interval of 2-3 km. Electrical resistivity survey was carried out using a Scintrex TSQ-3 transmitter along with a digital IP/Resistivity receiver. A Schlumberger array with a maximum current electrode spacing of 2 km was used.
Although an attempt was made to use larger current electrode spacing for deeper probing, output power limitations and low receiver sensitivity prohibited such operations to be carried out.

Vertical Electrical Sounding (VES) measurements were made along surveyed lines at accessible points. Apparent resistivity data were recorded corresponding to every electrode position as the array is expanded along the surveyed line. At each observation point a VES curve representing the vertical resistivity variation was obtained.

As mentioned above, accessibility and thick vegetation cover limited the density of resistivity observation points; requiring more field days and good condition logistics, especially good condition four-wheel drive vehicles and radio communication equipment. Nevertheless, 14 VES observations and 21 line km of resistivity profiling data was collected during the field season.

(b) Gravity and Magnetic Surveys

During the initial stage of the survey, a base station network was established in the survey area. A base connection between an existing main base station at Sodo High School and a point at the Bedessa river bridge was made in two loops. Other subsequent secondary and tertiary sub-base stations were later established in Anka (BS2) and about 7 km south of Dimtu, along the Dimtu-Chericho road (BS1), (Fig.27).

In a second stage, gravity and magnetic data acquisition surveys started from and closed to any one of the above sub-base stations. Measurements along regional routes of Bedessa-Fango-Dimtu, Bedessa-Anka-Bilate, and Dimtu-Chericho were made every 2 km.

On the other hand, a measurement interval of 1 km was used along the survey line from Anka village up to the strong fumarolic activity site of Anka Duguna. Detail gravity survey was conducted along surveyed lines (profiles 1-4) with a measurement interval of 500 m (Fig.27). Moreover, detail magnetic survey was carried out along profiles 1-6 at an interval of 100 m. The positions of semi-regional gravity stations were determined using a Trimble handheld GPS receiver and a handheld digital altimeter. The accuracy of horizontal position determination was ±30 m, while elevation of stations was accurate within ±3 m.
The gravity survey was conducted using a Lacoste and Romberg model G-780 gravimeter. The total field magnetic measurements were made using a Scintrex Integrated Geophysical System (IGS-2) magnetometer option. The positions of detail gravity, magnetics and resistivity observation points were determined using topographic surveying and tachometry.

2.3.3 DATA PROCESSING AND PRESENTATION

(i) DATA REDUCTION

Gravity data reductions which, included latitude, elevation (Free-air and Bouguer), and terrain corrections, were applied on the observed gravity data. Corrections due to topographic irregularities (hills and valleys) near gravity stations were applied by using a satellite digital terrain data of the study area and the terrain correction option of the "OASIS montaje" (Geosoft, 1999) application program. In this procedure, the station elevation data was merged and gridded with the satellite digital terrain data to produce a uniform grid cell size. By using this terrain data, the program computes the gravity corrections that must be applied on each observed gravity data.

Because of the random nature of the geophysical data (gravity, magnetics and resistivity), all have been gridded (interpolated) to produce a regular grid of the survey area, so that further frequency domain data processing can be applied. Hence, using the random gridding option of the "OASIS montaje " geophysical mapping system (Geosoft, 1999), the gravity and magnetic data were gridded at cell sizes of 500 m and 250 m respectively. As a result two grid maps; one showing the Bouguer gravity anomaly (Fig. 28) and another showing the total field magnetic anomaly (Fig.29) were compiled.
On the other hand, the apparent resistivity data for two electrode separations (AB/2 =100 m and 800 m) were also gridded using a cell size of 500m to produce the grid maps shown in figures 6 and 7 respectively.

(ii) ANOMALY SEPARATION
Analysis of the spectral plot (Fig.30) suggests that the regional Bouger gravity field (Fig.31) is characterized by a frequency band between $3 \times 10^{-5}$ cycles/m and $1.1 \times 10^{-4}$ cycles /m. In order to derive the regional field (Fig. 31), a band pass filter with the above frequencies was applied using the MAGMAP option of the "OASIS montaje", geophysical mapping system (Geosoft, 1999).
The residual gravity anomaly (Fig.32) is obtained by subtracting the regional field (Fig.31) from the observed Bouguer field (Fig.28). Largely, based on the spectral analysis depth estimate (Fig.30), the average depth of the regional gravity anomaly source is in the range of 2-3 km. For the residual anomaly, a source depth of less than one km was estimated. Similar spectral analysis was carried out on the total magnetic field (Fig. 29). However in this case, a high cut filter with a cutoff frequency of $1.2 \times 10^{-3}$ cycles/m was applied to reduce the effect of noise. Subsequently, a band pass filter of $5 \times 10^{-5}$ cycles/m to $10^{-4}$ cycles/m was used to obtain the regional magnetic field (Fig.33). From spectral analysis of the magnetic field, the average depth to the regional magnetic source is estimated to be 1-1.5 km.

Likewise, the residual (local) magnetic anomaly field (Fig.34) was obtained by subtracting the regional magnetic anomaly (Fig.33) from the total magnetic anomaly. The depth range of the residual anomaly source is between 500 - 1000 m.

**FIG. 30. RADIALLY AVERAGED POWER SPECTRUM OF THE BOUGUER GRAVITY FIELD, ABAYA GEOTHERMAL PROSPECT**
2.3.4 INTERPRETATION OF THE GEOPHYSICAL RESULTS

2.3.4.1 BOUGUER GRAVITY ANOMALIES

(i) ANOMALY DESCRIPTION

The Bouguer gravity anomaly map (Fig.28) of the survey area, in general, represents responses of near surface geological features superimposed on deep-seated structures. It indicates a number of prominent positive anomalies covering the southern and southeastern portion of study area and east of the Duguna - Fango volcanic mountain. The Bilate riverbed is mainly characterized by intense positive Bouguer anomaly.

Very high positive centers with an absolute gravity value of -60 mGal and more characterize the localities situated south of Fango Bijo and northeast of the Tobacco plantation. A NW-SE trending relatively wide positive gravity zone intersects the general NE-SW trend of the positive anomaly in the eastern part of the map. This zone covers the area east of the Bilate River, west of the Tobacco plantation extending across south of Fango Bijo up to Anka village in the west.

A large negative Bouguer anomaly (<-190 mGal) characterizes the map area corresponding to the Duguna Fango volcanic complex centered about the localities of Fango Damota and Fango Sore. In general, the northwestern portion of the map area is dominated by a relatively negative Bouguer anomaly with an absolute value of less than -170 mGal. The area east of Anka Shashara and near Anka village is represented by a circular negative gravity anomaly (-180 mGal).

(ii) GEOLOGIC AND TECTONIC INTERPRETATION

(a) REGIONAL GRAVITY ANOMALY

Referring to the regional gravity map (Fig.31), the southeastern and southern part of the study area is represented by a high gravity anomaly (>40 mGal) trending in a general NE-SW direction. It is centered in the area north of Chericho state farm and over the Tobacco plantation. This anomalous area, situated on both banks of the Bilate River, is covered by Quaternary basalts underlying lacustrine sediments.
The center of this high anomaly zone corresponds to the location of a hydrothermal manifestation (a group of hot springs) on the banks of the Bilate River. The NE-SW linear positive gravity trend observed on the map along the Bilate River might suggest that the Bilate River has formed along a NE-SW trending fissured structure with dense basaltic intrusion that has extruded to cover the surrounding area.

The implications of the proximity of most of the hydrothermal manifestations in Anka Duguna and near the Tobacco factory to the center of this regional gravity high might is not obvious. However, the regional low (Fig.31) trending NE-SW formed by a series of circular gravity depressions in Anka Shashara, Fango Sore, and Fango Damota and over the Duguna Fango volcano might correspond to deep-seated linear low-density zone. This feature might be interpreted as a weak zone of regional tectonic structure through which the large volcanic rhyolitic center, the Duguna-Fango, has erupted to the surface.
FIG. 31 REGIONAL GRAVITY MAP OF THE NORTHERN ABAYA GEOTHERMAL PROSPECT

The extensive alteration zone and hot ground near Anka village, Anka Damota and the Dimtu hot spring are situated within this low gravity anomaly zone. Surface geological mapping indicates that Quaternary rhyolitic flows and pumiceous pyroclastic deposits mainly cover the latter region of low gravity anomaly. Such surface low density formations can result in the observed circular low gravity depressions observed on the residual (local) anomaly map (Fig.32), however, cannot explain the deep seated (3-4 km) linear low of the regional field.
(b) RESIDUAL (LOCAL) GRAVITY ANOMALY

The residual Bouguer gravity anomaly map (Fig.32) shows a number of high and low gravity anomaly zones and trends.

FIG. 32. RESIDUAL GRAVITY MAP OF THE NORTHERN ABAYA GEOTHERMAL PROSPECT

The first and most prominent zone corresponds to a NW-SE trending gravity ridge (>40 mGal) stretching from the Tobacco plantation on the right bank of the Bilate River, across Fango Bijo and unto Anka village in the west. This anomaly has two aligned peaks south of the Duguna - Fango volcano. The southwestern flank of this high gravity zone is characterized by a trough following the same NW-SE trend. On the other hand, the northeastern boundary of this anomaly trend is represented as a linear gravity low with a similar NW-SE orientation.
The above positive anomaly zone may be attributed to a regional tectonic structure that is transverse to the normal NE-SW Wonji Fault Belt elements mapped in the study area. Its spatial occurrence corresponds to observed Wonji Fault elements in the southwestern flank of the anomaly. The hydrothermal manifestations of Anka Duguna lie within this zone of anomaly. Its northwestern edge hosts the large altered and hot ground of Anka Duguna.

From spectral analysis, the average depth of the above important positive gravity anomaly source is inferred to be less than 1 km and may be due to a transverse tectonic structure. The SE extension of the anomaly up to the Bilate River across the Tobacco factory seems to be closely associated with the hydrothermal manifestation consisting of a group of hot springs in the area.

The second important anomalous zone is a positive gravity ridge (> 40 mGal) that runs from northwest of the Tobacco plantation in a NE direction up to Dimtu village. Being adjacent to the eastern flank of the Duguna-Fango volcano, this anomaly may be attributed to a NE-SW Wonji Fault belt element intruded by dense basaltic flow. The Dimtu hot spring situated on the right bank of the Bilate River, just north of the village, is associated with the northeastern edge of this linear positive gravity anomaly.

The third anomalous feature observed on the residual gravity map (Fig.32) is the great gravity low corresponding to the Duguna-Fango volcanic complex. The anomaly is centered between the localities of Fango Sore and Fango Damota. This anomaly is considered to reflect the thick sequence of surface mapped pumiceous pyroclastic deposits that have been produced by the Duguna volcano. The whole area north and northwest of the areas of Fango Bijo and Dimtu is characterized by a similar low gravity anomaly.

2.3.4.2 MAGNETIC ANOMALIES

(I) ANOMALY DESCRIPTION AND INTERPRETATION

The total magnetic field map (Fig.29) of the study area is dominated, mainly, by two positive anomalous zones, one trending almost E-W and the other NE-SW.
The E-W trending positive anomaly extends from the Bilate River (Tobacco factory) traversing across Fango Bijo, Anka Duguna up to Bedessa town. The anomaly covers parts of the Duguna-Fango volcano. The causative geologic feature of this dominant anomaly is expected to be in a depth range of 1-2 km (spectral analysis).

![Image of Total L Magnetic Map](image)

**FIG. 29. TOTAL L MAGNETIC MAP OF THE NORTHERN ABAYA GEOTHERMAL PROSPECT**

The second most important anomalous feature is a NE-SW trending positive magnetic feature, discontinuous at places, i.e., west of the Chericho State Farm, south of the Tobacco factory. The anomaly characterizes the southern and eastern portion of the map area. It stretches from south of Chericho State Farm up to Dimtu village in the NE. The position of the E-W trending high magnetic anomaly corresponds to Quaternary basalt flows at its eastern edge. Its central and western portion corresponds mainly to rhyolitic flows and young pumiceous pyroclastic deposits.
The anomaly may be attributed to a relatively deep-seated (within 1 km) magnetic structure associated with a dense intrusion.

The regional magnetic map (Fig.33) clearly shows a high magnetic anomaly zone that extends in a nearly E-W direction from the Bilate River in the east up to Bedessa in the west. On the other hand the low magnetic relief observed on both the total and the regional magnetic maps (Fig.29 and 33) corresponding to the summit of the Duguna-Fango volcano, in the localities of Duguna Mariam and Fango Giorgis, reflect thick pyroclastic deposit and volcano-sediments.

FIG. 34. RESIDUAL MAGNETIC MAP OF THE NORTHERN ABAYA GEOTHERMAL PROSPECT
The linear magnetic high trend following the Bilate River course (Fig.33) may suggest that the river flows along a zone of tectonic weakness having a basaltic intrusion from depth.

Furthermore, the fact that all hydrothermal manifestations lie within zones of low magnetic relief (Fig.33) may suggest that the anomaly zone expresses a tectonic structure through which geothermal fluid circulation occurs.

Largely, the results of both the gravity and magnetic surveys have indicated clear regional tectonic structures having a depth extent of 1-3 km in association of the observed surface hydrothermal manifestations.

However, interpretations of gravity and magnetic anomalies are the most possible explanations that can be provided based on the available geological and tectonic data. Relatively more constrained interpretations can be made with more geological and geophysical data.

### 2.3.4.3 RESISTIVITY ANOMALIES

#### (i) APPARENT RESISTIVITY MAPS

The resistivity data is presented in the form of apparent resistivity maps and geo-electric sections. Apparent resistivity maps for electrode separations of $AB/2 = 100$ m and $AB/2 = 800$ m have been compiled.

**Apparent resistivity Map for $AB/2 = 100$ m.**

This map (Fig.35) shows the resistivity distribution of the near surface geologic units. A clear high resistivity (>230 Ohm-m) anomaly trends in NE-SW direction and spatially corresponds to a relatively elevated ridge of rhyolitic flow. The anomaly may be attributed to NE-SW trending Wonji Fault elements south of Fango Bijo and east of the locality of Anka Duguna.

Another significant resistivity anomaly zone occurs in the northeastern portion of the map. It is characterized by a relatively high resistivity with a maximum of 230 Ohm-m. The anomaly is located south of Dimtu village and east of Fango-Damota and trends in a NW-SE direction.
At the surface, this anomaly corresponds to Quaternary lacustrine sediments underlain by Tena Bialte basalts. On the other hand, two major resistivity zones are observed on this map (Fig.35) in the west, northwest, south and southeast. The one in the south and southwest covers the Tobacco Plantation area. The west and northwestern low resistivity zone includes the localities of Anka Duguna and west of Fango Bijo and the Duguna volcano which are covered by lacustrine and volcano sediments underlain by Tena Bilate basalts. Hydrothermal alteration zones in the western part of the study area lie within this low resistivity region (Fig.35)

In summary, low-lying parts of the study area covered by quaternary lacustrine and volcano sediments are characterized by low resistivity (5-40 Ohm). The Tobacco plantation area and the alteration zones in Anka Duguna area are in this zone. On the other hand the relatively high areas striking N-S located east of Anka Duguna, west of the Tobacco Plantation and Chericho State Farm and south of Fango Bijo have a relatively high characteristic resistivity (160-230 Ohm-m) corresponding to near surface and outcropping volcanic rocks mainly quaternary rhyolites and basalts.

**FIG.35 APPARENT RESISTIVITY MAP (AB/2=100 m) IN NORTHERN ABAYA GEOTHERMAL PROSPECT**
(ii) Apparent Resistivity Map for AB/2 = 800 m.

Fig. 36 shows the resistivity distribution corresponding to current electrode separation of AB/2 = 800 m. This electrode separation is regarded to attain a probing depth of 500-800 m below ground surface. Hence, the measured resistivity is expected to represent the response from geologic formations within the above depth range.

![Apparent Resistivity Map (AB/2=800m) in Northern Abaya Geothermal Prospect](image)

**FIG.36. APPARENT RESISTIVITY MAP (AB/2=800m) IN NORTHERN ABAYA GEOTHERMAL PROSPECT**

One of the conspicuous anomaly zones in the map stretches from the area situated between east of Anka Duguna and west of Chericho State Farm in the south up to the summit of the Duguna-Fango volcanic complex in the north. This is a relatively high resistivity (40-80 Ohm-m) zone corresponding to mapped N-S to NE-SW discontinuous low amplitude fault scarps and tectonic structures mainly formed of rhyolitic flows.
The anomaly zone is flanked on both the west and east by a relatively low resistivity zone. The western low resistivity anomaly zone includes the hot ground and hydrothermal alteration zones at the southwestern foot of the Duguna Fango volcano and the strong fumarolic activity localities of Anka Duguna in the south. The eastern anomaly zone on the map includes the Tobacco Plantation area west of the Bilate River.

In general, the results of the resistivity survey suggest that there is good correlation of observed low resistivity anomaly zones with surface mapped hydrothermal manifestations. Hence, the areas of Anka Duguna and the south west of the Duguna-Fango require further detail resistivity survey. In this regard, future geophysical survey should consider extension of profile 3 to west; profile six both to the west and east; profile four to both the west and east.

In general, the geoelectric section along profile 3 suggests a relatively deep alteration zone (greater than 400 m) on its western end. A relatively thick saturated zone below a depth of 50 -75 m from the central part up to its eastern edge, characterized by a low resistivity range (12-23 Ohm-m) is regarded to be due to vesicular basalt flows and an underlying pumiceous pyroclastic deposits.

### 2.3.5 SUMMARY OF THE RESULTS

The integrated geophysical survey conducted in the prospect area has elucidated a number of facts about the subsurface geological and tectonic conditions in the study area, especially in relation to the heat source and the possible mode of geothermal fluid circulation. As a result of this investigations the following main conclusions have been arrived:

- A relatively wide and linear low gravity zone, clearly expressed on the regional magnetic map (Fig. 9) may be attributed to a major NE-SW Wonj Fault element through which the Duguna - Fango volcanic complex may have erupted. This zone is expressed on the residual magnetic map (Fig.13) as a quiet zone.
- The regional linear gravity low response implies a low-density zone probably corresponding to deep-seated alteration zone. This anomaly trend is interpreted as a weak tectonic zone and is denoted by F5 on the interpretation map (Fig.37).
- The relatively wide alteration zone in the southwestern foot of the Duguna-Fango volcano is located within the above low density zone (F5)
- A second NNE-SSW tectonic structure (F3) that is clearly expressed on the residual magnetic map (Fig.13) as a low magnetic relief connects the above major NE-SW Dimtu-

  Duguna-Anka low-density structure. This structure (F3) is in close correspondence with NNE-SSW mapped surface structures in the study area (Fig.37).
A third, nearly N-S trending linear low magnetic anomaly zone is also interpreted as expressing a tectonic structure (F4). The position and orientation of this zone is in correspondence with surface mapped geological structure near Anka Shashara, although the magnetic anomaly extends far more to the north.

Two nearly parallel NW-SE linear magnetic anomalies (Fig.13) shown on the interpretation map (Fig.17) as F1 and F2 are characterized by a low magnetic relief. These anomaly trends are attributed to NW-SE transverse tectonic structures transecting and offsetting the NE-SW Wonji Fault elements mapped in the study area (Fig.17). Both structures extend from the...
localities of Anka and Anka Shashara in the NNW up to the Bilate River in the SSE of the map area. These structures connect a number of NE-SW Wonji Fault belt elements including the major NE-SW structure through which the Duguna-Fango volcano has erupted. Almost all surface hydrothermal manifestations in the survey area are located within this intersection zone (Fig17).

- In view of the above conclusion inferred from the magnetics and gravity results, it can be further concluded that the main heat source being beneath the Duguna-Fang volcano, F3, F4, F5 allow N, NE-SW geothermal fluid circulations while F1 and F2 being connected to this main structure (F5) act as a geothermal fluid conduits in a NW-SE direction. This conclusion is in agreement with the location of hydrothermal manifestations in the study area.

- The Bilate riverbed and its banks are characterized by both gravity and magnetic high trends (NE-SW). These anomaly magnitudes and trends suggest a fissured structure through which dense basaltic lava has extruded covering the surroundings of the river.

- Due to thick vegetation cover, rugged topography and time constraint, the resistivity survey did not cover as much area as the magnetic and gravity surveys. However, an adequate result has been achieved from the survey. A low resistivity anomaly zone on the west covering Anka Duguna up to the southwestern foot of the Duguna-Fango volcano is associated with a long alteration zone. A central N-S trending high resistivity zone corresponds to small rhyolitic fault scraps of the N-S Wonji Fault belt elements.

- Nevertheless, apparent resistivity mapping with larger current electrode spacing (AB/2 > 1000 m) is considered to provide a clear picture of the resistivity distribution of the deeper subsurface if a high power output transmitter and sensitive receiver are used. The fact that the present survey was limited to current electrode spacing less than 1000 m. meant shallower probing depth (of the order of 500-800 m)

- The results indicated on the geo-electric sections, magnetic and gravity profiles (Fig.14, 15 and 16) discern the lateral and vertical distribution of resistivity along profiles 1,2,3 and 6. A number of tectonic structures observed on the magnetic and gravity maps are noted by these sections.
3. CONCLUSIONS AND RECOMMENDATIONS

Based on an integrated geothermal resource exploration program carried out from 1991 E.C - 1993 E.C in two prospects within the Main Ethiopian Rift, i.e. Tulu Moye-Gedemsan and Abaya, geological, Geochemical and geophysical results have confirmed a number of hydrothermal systems of potential geothermal energy resource that require further detail work including shallow temperature gradient and exploratory deep drilling. Consequently, the following conclusions and recommendations are made for each of the prospect area:

Results of geological, geochemical and geophysical studies conducted in the Abaya geothermal prospect so far suggest that future detail studies in the prospect area, including geophysical investigations and drilling of shallow temperature gradient and deep exploratory wells, are recommended to concentrate in NW Abaya Fault area, Anka Bilbo, Wache and Bolcho areas. The result of the geophysical investigation conducted in the Anka Bilbo and Chericho areas suggests, further exploration work including drilling should be conducted the localities of Anka Duguna, Chericho and the tobacco factory. However, this does not exclude additional geophysical work including magnetics, gravity and electrical resistivity surveys along regular grids up to the Chericha volcanic center in the east and Korke volcanic center in the west.
REFERENCES


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