GEOLOGY AND GEOTHERMAL RESOURCES OF THE NORTHERN LAKE ABAYA AREA (ETHIOPIA)

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ABSTRACT

The Northern Lake Abaya area located in the southern part of the Main Ethiopian Rift (MER) encloses a variety of manifestations that indicate the existence of economically exploitable geothermal resources. Tertiary volcanic succession has been down faulted into the rift floor and in part is covered by the rift valley lakes such as Lake Abaya. The formation of the MER was accompanied by late Pliocene rift shoulder volcanic activity from centers such as Damota predominantly made up of trachytic lava, and rift margin rhyolitic volcanic complexes which produced extensive ignimbrite succession now exposed along the rift escarpments. During the Quaternary period the extensional axis of the MER became the locus of volcanic activity with a bimodal basalt – rhyolite extrusion in the rift floor. It is evident that shallow crustal magma chambers feeding felsic volcanic complexes such as Duguna Fango, Salwa Dore - Hako, Chericho, Kilisa and Donga provide the heat for the hydrothermal system which reside in Pliocene volcanic formations and are capped by Quaternary lacustrine and volcanoclastic sediments. Lake Abaya forms a closed drainage basin with adjacent plateau receiving over 1500 mm of average precipitation maintains a stable recharge for the prevailing hydrothermal system. Regional ground water flow direction in the study area is to the southwest following Bilate River which is the major river draining into the lake and parallel to the major NNE - SSW structural fabric of the rift which provides secondary permeability.

Three hydrothermal fields exist in the study area, a hydrothermal field around the Duguna Fango volcanic complex with manifestations at Bilbo, tobacco plantation and Dimtu has strong volcanological supportive features despite lower inferred reservoir fluid geochemical geothermometer temperatures. About 40 km to the southwest two other hydrothermal fields (Northwest Abaya fault and Bolcho-Northeast Abaya respectively) are located at a latitudinal distance of about 20 kms between each other. The northwest Abaya fault hydrothermal field with the most profuse hydrothermal manifestations probably derives its heat from the SalwaDore – Hako and Obitcha volcanic centers to the north. This field despite no nearby prominent volcanic features as a heat source discharge mature waters with higher fluid geochemical geothermometer temperatures. Across the Chewkare graben the Bolcho and northeast Abaya hydrothermal fields located in a hydrologically most favorable location between Bilate and Gidabo rivers show a variety of hydrothermal manifestations indicating the existence of high-enthalpy geothermal reservoir related to the cluster of felsic volcanic centers such as Chericho, Kilisa, Donga and Werencha. Fluid geochemical data on high temperature springs also suggests the existence of at least two distinct hydrothermal reservoirs in the study area. If on the contrary the fluids have the same origin it can be speculated that an upflow zone of an advective hydrothermal system located to the north has out flows to the south at the northern shores of Lake Abaya which is the hydrologic depocenter. However future geoscientifuc studies should also evaluate data in light of the model of regionally layered reservoirs (intermediate T overlying a high T reservoir) proposed for the northern MER to explain the occurrence of both $T > 65°C$ and $T < 65°C$ spring systems in close proximity to each other albeit mixing models at margins of an advective hydrothermal system.

1. INTRODUCTION

The northern Lake Abaya area is located in the southern part of the Main Ethiopian Rift (MER, fig 1) and is accessible on the Addis Ababa - Shashemene – Woliata Sodo - Arba Minch all weather road. Other important secondary roads descending down into the rift floor from this trunk road such as the Sodo-Bedesa-Dimtu road and the Humbo-Abela Fericho-Abaya state Farm road provide accesses within the study area. Other secondary roads exist in the intensely cultivated parts along the escarpments and connecting the mechanized plantations along the Bilate River flood plain in the rift floor (fig 2).

In the study area the western escarpment of the MER slopes down along a series of normal faults from an average elevation of about 2000m a.s.l. (with only the Pliocene Damota volcano rising to 2950 m a.s.l.) to 1169m a.s.l. at the level of Lake Abaya. A vertical displacement of 1000 m was observed on a single fault making the western escarpment of the Ganjuli Graben (Lake Abaya) with preserved evidences of recent movements along the fault plane south of the study area (James 1972; Zanettin et al., 1978). The rift floor is characterized by a series of normal faults with predominantly NNE-SSW trend forming horsts and grabens along the rift axis. Recent volcanism in the rift floor is marked by several complex volcanic centers and fissural basaltic eruptions. The most prominent volcano is Duguna-Fango which rises over 1000m from the rift floor and other felsic centers which rise about 500 m above the average rift floor level include Chericha, SalwaDore, Hako, Donga (Simbura), Obicha and Werencha (fig 3). A closed drainage system exists within the study area, with Hamesa River and its tributaries draining the western part of the study area into Lake Abaya. The central and northern part of the study area is drained by Bilate River and its tributaries such as Bisare and Derba while Gidabo and Gelana Rivers drain the southeastern part of the study area into the lake. Shallow ground water flow in the region probably also converges towards Lake Abaya with a major north to south component.

The western escarpment belongs to the *Weyna Dega* agro-ecological zone (mean annual temperature and rain fall of 19°C and 1500 mm respectively) whereas the rift floor belongs to the *Kola* zone (mean annual temperature and rain fall of 23°C and 700 mm respectively) (EMA, 1988). Unlike the rift floor which has a thick soil cover derived from the lacustrine and alluvial sediments the escarpments are mantled by a thick latertic soil and as low crop risk zone is intensely cultivated and densely populated with a farming and pastoral system of the Enset Culture. Mechanized irrigation systems are wide spread in the rift floor to grow a variety of cash crops (cotton, tobacco, fruits). The natural vegetation where preserved is open bush land and wooded grass land with particularly acacia trees in the rift floor and broad leafed forest on the escarpments.

In conjunction with geologic mapping using 1:50,000 scale topographic base maps and 1:60,000 scale aerial photos the structural controls and extent of active and fossil hydrothermally altered grounds were noted. Secondary minerals were characterized and observations made on the source and type of the altering fluid. Representative samples were collected from map units for petrographic studies. In all localities of hydrothermal manifestation discharge of springs, and pressure of fumaroles estimated, temperature measurements were done using a maximum thermometer, pH of spring discharge measured using a phanphea paper.

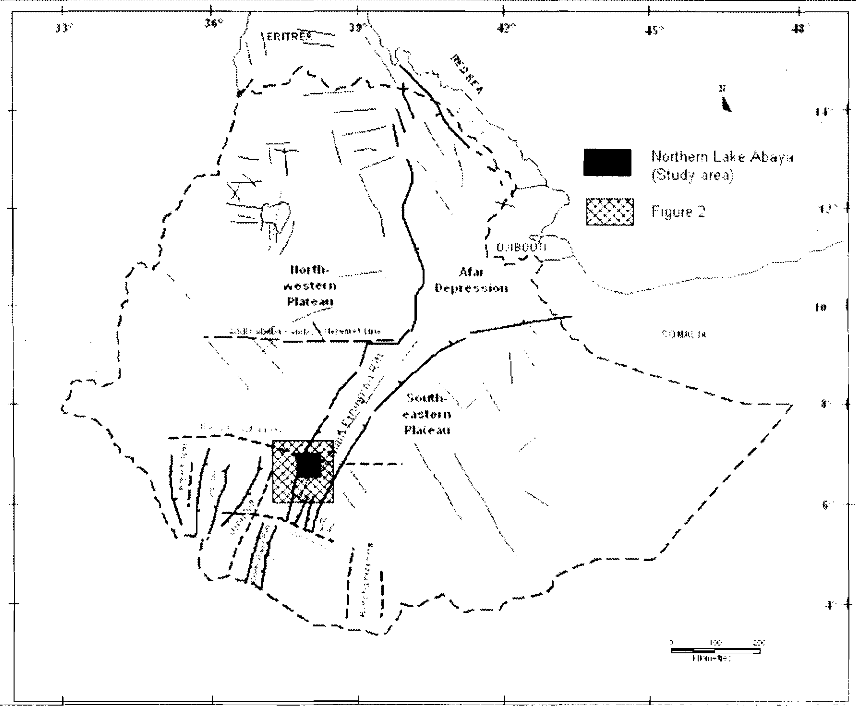

Figure 1: Location map of the study area with major regional structures.

The southern part of the MER has a more recent volcano-tectonic history consistent with the proposed north to south migration of volcano-tectonic activity in the Ethiopian Cenozoic volcanic province (Kazmin, 1979). It is widely accepted that initial sagging of the MER started about 10 Ma by the faulting of the pre-rift volcanic succession with other important rifting events around 5-4 Ma and in the Quaternary. During the Quaternary the segments of the active volcano-tectonic axes known as the Wonji Fault Belt (WFB) formed. The southern most segment of the WFB is found in the study area north of Lake Abaya and hosts the Quaternary felsic central volcanic complexes which straddle on a sequence of volcanic products and lacustrine deposits of Plio-Pleistocene age. Both lava flows and pyroclastic products have been extruded from the complex volcanic centers in the study area and their deep seated magma chambers are heat sources for the hydrothermal activity in the region.

Geologic studies has established a regional statigraphic frame work (Kazmin and Berhe, 1981, UNDP, 1987) for the MER. Pre-rift flood basalt succession with minor sialic members (Jima Volcanics, Teferra et al., 1996) unconformably resting on the Precambrian Basement are exposed on the western plateau and the escarpments and form the sub-basement in the study area. This volcanic sub-basement is overlain by a Mio-Pliocene (9-2 Ma) succession comprised predominantly of ignimbrites with other pyroclastic deposits, rhyolitic and trachytic lava flows, domes (Nazret Group). The Nazret Group volcanic products are exposed over an oval shaped area surrounding the MER along the rift margin and escarpments. In the rift floor the Nazret Group is overlain by a succession of flood basalts of Pliocene age (Bofa Basalts) which attain a thickness of several hundreds of meters as confirmed by the deep geothermal exploration drilling at Aluto-Langeno. The Bofa Basalts are in turn overlain by the Quaternary bimodal transitional basalt / peralkaline felsic volcanic products of the Wonji Group. The

Volcanic products of the Wonji Group (including those from the axial volcanic centers) are intimately associated with lacustrine sediments related to the more extensive ancestral lake(s) on the rift floor in the pluvial periods of the Pleistocene.

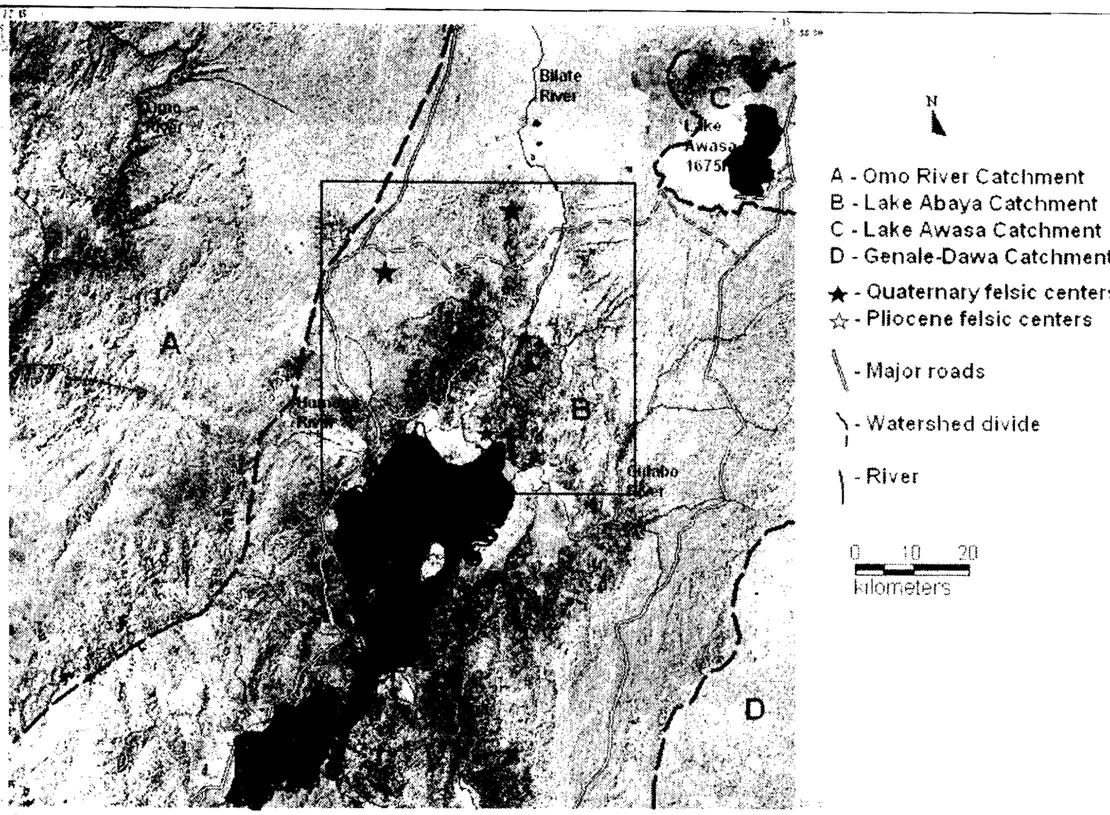

Figure 2: Landsat TM+ color composite (bands 1,2,3) of the study area (square) and surrounding. Bilate and Gidabo rivers are shown within the study area; broken line delineates the Lake Abaya catchement. Omo River on the northwestern corner of the image is also the major river draining the region.

Analysis of satellite lineaments from landsat imagery shows four major lineament sets (Fig. 3; Abebe et al., 1992) which can be grouped as rift related and none related. The most frequent N10-20°E lineament set are related to the Quaternary episode of volcano-tectonism along the axis of the rift, whereas a NE-SW lineament set corresponds to the azimuth of the border faults and are related the initial phase of graben formation. Hydrothermal fluid circulation the study area appears to be controlled by these two rift related lineament sets. Among the other two lineament sets which are not rift related is a N10°W lineament set probably is a successor of Precambrian structures where as an E-W trending lineament set appears to be a result of Tertiary flood basalt volcanism.

Previous studies on the geothermal resources within the broader lakes district rift have indicated that convective hot water systems exist beneath a cap rock of rift floor lacustrine and volcanoclastic sediments with heat being derived from the magam chambers feeding the Quaternary rhyolitic volcanic complexes along the axis of the MER. The reservoir inferred to be within the upper units of the Tertiary volcanic sequence (predominantly ignimbrites) exposed on the escarpments has been down thrown into the rift floor (Lloyd, 1977). Volume of felsic volcanic rocks extruded from within the prospect during the Quaternary period is over 200 km³ out of which about 100km³ is from Duguna- Fango volcanic complex. Eventhogh there are evidences showing that there were vigorous hydrothermal manifestations in the past the area belongs to a group of systems which now discharge about 10MW of heat energy in the East African Rift (Hochstein, 2005). Volume of contemporaneous basaltic magma erupted may be difficult to quantify is however comparable to the felsic lava.

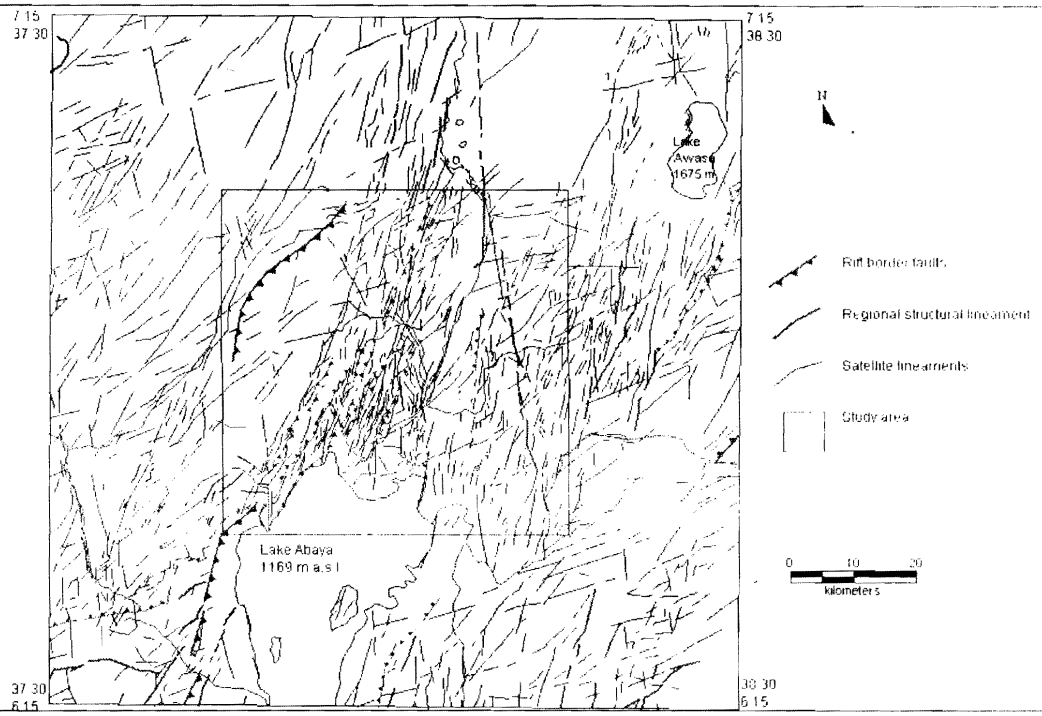

Figure 3: Lineament pattern from Landsat imagery of the northern Lake Abaya area and surroundings (from Abebe et al., 1992).

The northern Lake Abaya area have hot springs discharging near boiling alkaline chloride and steam heated acid sulfate waters with high CO_2 content and inferred reservoir solute geothermometer temperatures ranging between 177°C and 265°C and gas geothermometer temperatures which range between 111°C and 169°C (Craig, 1975; Glover, 1976). Geophysical survey (VES – 58 observations and SP – 30 line km) and gravity survey (130 line km) conducted suggested the existence of economically attractive hydrothermal resources in the area. The electrical resistivity survey was interpreted as a 3-Layer model defined a high resistivity top layer (20-1500 Ωm) to be underlain by a low resistivity intermediate layer (1-8 Ωm) and a high resistivity basement indicating that hydrothermal fluid are brought from below the depth of the basement to show a well defined low resistivity anomaly in the northwestern shores of Lake Abaya (Tezcan et al., 1983). The study recommended exploration drilling and hence the prospect was one of the three candidates to be explored by deep drilling during the Geothermal Drilling Project (Lakes District) in the 1980's.

STRATIGRAPHIC OUTLINE

Pre-rift Basalts (Tb_1)

Volcanic sub-basement in the study area is an intensely jointed, and spheriodically weathered basalt which cropsout on the series of faults forming the western escarpment of the Ganjuli Graben. This basaltic sub-basement is conformably overlain by Chewkare ignimbrite (Ti) and its association with rhyolitic ignimbrites suggests that it is correlable with Jima Volcanics or the Main Volcanic Sequence with an absolute K-Ar age range of 42.7-30.5 Ma (Davidson, 1983).

2.2. Chewkare Ignimbrites (Ti)

A succession of ignimbrite flows exposed on the west Abaya fault forming the western margin of the Chewkare Graben (axial graben occupied by Lake Abaya / northern Ganjuli Graben) are named as the Chewkare Ignimbrites. The Chewkare Ignimbrites are brownish and grayish green, crystal rich ignimbrites locally showing cooling joints, with exposed thickness of upto 100m. The Chewkare Ignimbrites are overlain by the lacustrine sediments (Ql_1) with intercalations of Quaternary basalts. Reported isotopic age for the ignimbrites is 4.4 Ma (EIGS-GEP, 1980) which makes them correlable with Nazret Group Ignimbrites of the northern and central MER and together with intercalated Pliocene rift floor basalts (Bonkaka / Bofa basalts) are the likely reservoir rocks for the prevailing hydrotheramal system(s) in the study area.

2.3. Damota Trachyte (Tt_2)

Trachytic lava flows from the Damota volcanic complex which rises for over 1000 m from the surrounding rift escarpment represents rift margin volcanism in the late stage of rift development along transverse lines such as the Addis Ababa – Ambo – Nekemet Line (which host centers such as Yerer, Wechecha and Furi) and the Bonga – Goba Line which hosts Damota. Alkaline basalt magmatism related to such transverse structures of the rift are probable parents to such lava (Chernet 1995), and provide a unifying theme in the petrogenesis of felsic volcanism in the MER and the Afar. A similar cross rift fault with a displacement of about 500m to the north has been reported about 70 km to the south (Dita – Mirab Abaya lineament James, 1972). On Damota exposures of light greenish gray, porphritic (anorthoclase) trachyte with cooling joints are more weathered near the flanks of the shield than near the summit. No absolute isotopic age determination exists for Damota, but it has been generally accepted that it is correlable to rift shoulder centers in the northern MER and hence its Pliocene age. Damota however shows more youthful features which suggests that activity may have continued into the Quaternary.

2.4. Quaternary Ignimbrites (Qi)

The western 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 several tens of meters of this 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 by in large older than the lacustrine sediments. Quaternary ignimbrites also crop out on the eastern part of the study area and are related to earlier caldera forming pyroclastic eruptions from centers such as Obicha and Simbura.

Figure.4: Geologic map of the study area.

2.5. Quaternary Basalts (Qb_1 and Qb_2)

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 (Ql_1). Even though distinguished primarily on the basis of degree of preservation of volcanic structures and intensity of post-emplacement tectonic movements of the flows rather than petrologic or geochronologic evidence two Quaternary basalt members (Qb_1 and Qb_2) were mapped. The first pulse of basaltic effusion (Qb_1) 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. The younger episode of basaltic eruptions crops out along an axial zone of more recent volcano-tectonic activity of the northwest Abaya hydrothermal field.

2.6. Rhyolitic Volcanic Centers (Qr_1, Qr_2 and Qr_3)

Quaternary rhyolitic volcanic centers which straddle along the active volcano-tectonic axis of the rift have produced large volumes of peralkaline lava flows (Qr_1, Qr_2 and Qr_3) and pyroclastic deposits (Qp) with earlier members intercalated with lacustrine sediments. Obitcha rhyolitic center with a horse shoe shaped caldera structure and a diameter of 10 km is situated off the active axis of the rift adjacent to Damota volcano. Large volumes of lava and pyroclastic products are exposed on the flanks and caldera rim of the volcano. A K-Ar age of 1.57 Ma has been reported for a rhyolite flow (Qr_1) from the inner caldera wall of Obitcha (EIGS-GEP, 1979) and probably represents the earliest phase of rhyolitic volcanism in the study area. Duguna Fango volcanic complex is the most prominent of the Quaternary volcanic centers with a base diameter of about 10 km and a summit caldera which produced pumice and ash fall deposits (Qp) which attain a thickness of over 30 m in the summit caldera. The Salwa Dore – Hako rhyolitic center have produced very recent obsidian and pitchstone flows probably representing the youngest rhyolitic activity (Qr_3) in the study area. Other rhyolitic volcanic centers include Simbura (Donga) rhyolitic volcanic complex which rises about 300 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. Stratified pyroclastic layers which gently dip to the northeast, and other field observations suggest a caldera collapse structure with a displacement in excess of 500mts. The complete circular outline of the collapse structure is marked by smaller rhyolite domes to the southeast which probably acted as a hinge during the caldera subsidence. Chericha whose near perfect cone rises about 500 m from the rift floor with a classic summit caldera a few kms in diameter and other minor rhyolite flows and domes such as Kilisa, Donga, Werencha and Chama are found along the axis of the rift.

2.7. Lacustrine Sediments (Ql_1, and Ql_2)

Horizontally bedded yellowish brown poorly indurated siltstone, mudstone with interbedded reworked and waterlain pumice and ash crop out over a wide area north of Lake Abaya. Two major lacustrine sedimentary units (Ql_1 and Ql_2) were characterized. The earlier unit (Ql_1) related to the pluvial periods of the Pleistocene cover a wide area north of the lake and crop out upto 1700 m a.s.l. elevation near Bedesa town over 500 m above the present lake level. Quaternary rhyolitic centers have supplied large quantities of pyroclastic material to the lake basin which was deposited with out much reworking. Some of the rhyolitic volcanic complexes formed islands in this high level ancestral lake, while some like Obitcha were totally submerged for lacustrine sediments to be deposited within the caldera floor. Contemporaneous to the first phase of lacustrine sedimentation basaltic eruptions are evident in many sections. The second phase of lacustrine sedimentary unit (Ql_2) is related to fluctuations of the present Lake Abaya level during the Holocene and is restricted to the vicinity of the lake. The fact that the lacustrine sediments provide an effective cap-rock is evident on figure 5 where gradient of DN values of thermal infra-red image shows lowest values.

2.8. Alluvium (Qal)

The lower courses of two major rivers (Bilate and Gidabo) which drain most of the study area into Lake Abaya are covered by fluvial deposits along its gentler course. Both Bilate and Gidabo Rivers have formed lacustrine deltas a few kilometers wide on the northern part of Lake Abaya. Colluvial and outwash debris are found widespread in the study area particularly along foothills of major fault scarps.

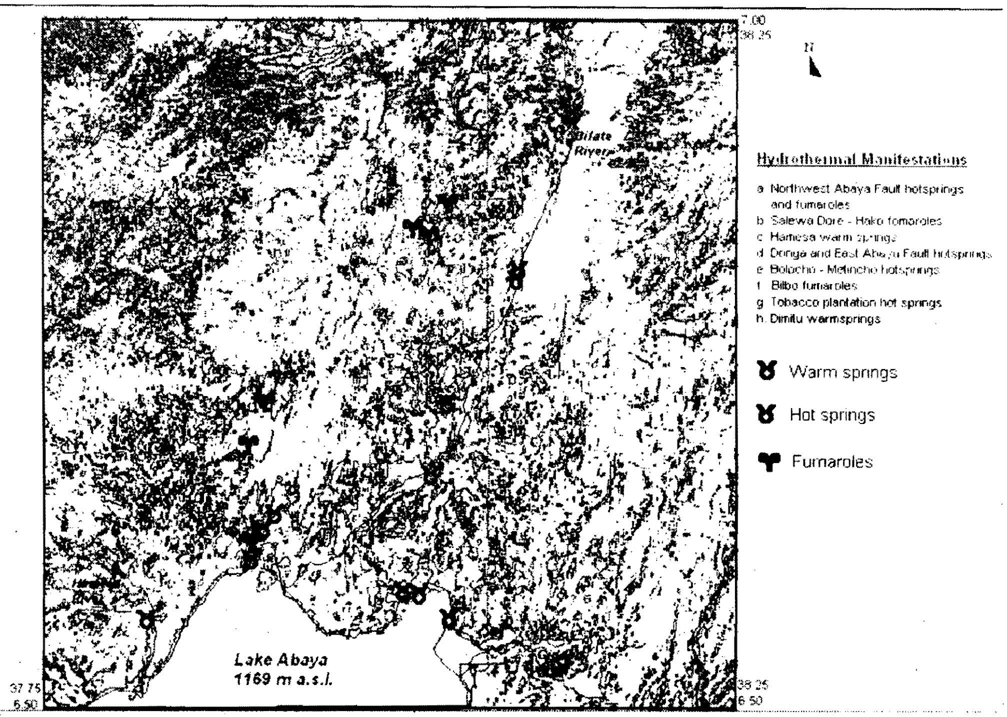

Figure 4: Gradient of DN values of thermal infra red image of the northern Lake Abaya area with hydrothermal manifestation shown as symbols. Note low values over the cap-rock (lacustrine sediments} and Lake Abaya..

3. HYDROTHERMAL MANIFESTATIONS

The distribution of active hydrothermal manifestations show strong control by structural fabric and hydrogeologic conditions with most hot springs found near riverbeds or present lake level suggesting more heat out flow by the sub lacustrine thermal spring activity.

1. Northwest Abaya Fault hot springs and fumaroles are located along about 2kms length of the Northwest Abaya Fault where about a dozen hotsprings and fumaroles form the most vigorous thermal manifestation in the study area. The springs and fumaroles emerge from near the base of the western boundary fault of the Cherwkare Graben and discharge near the shores of the lake, forming pools as big as 5m in diameter and nearby a widespread unstable swampy shore of Bora Mita (meaning swallows a bull). Spring #6 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 confirmed by the invasion of many man made structures by the lake. The perched acid spring #7 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 have 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 near 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 discharge of thermal water in the past.

2. Salwa Dore and Hako domes (Qr_3) are located in a NNE-SSW trending graben about 3 km wide and 5 km long (SalwaDore-Hako Graben). At the summit of SalwaDore numerous weak steam vents from within the blocky glassy bare rocks discharge steam at about 90°C. Hydrothermal alteration is minor and restricted to the vicinity of the vents. Similarly at the summit of Hako from a deep joint within the recent pitchstone weak steam inhalations discharge steam at a temperature of 42-43°C near the vents.

3 Hamesa warm springs are located on the Woliata Sodo-Arba Minch road about 20 km south of Humbo town. From near the riverbed and a contact between the Tertiary ignimbrites and the Quaternary Basalt a number of springs discharge near neutral pH water at 30-35°C. Located near by a major road and scenic falls of Hamesa River and warm temperature with mild chemistry the springs are legible to be developed as a resort.

4. Donga and East Abaya hot spring are group of warm springs 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 group of springs discharge into the lake and surrounding swamp. Overall discharge from the group of springs is substantial and difficult to estimate but has formed a shallow water body with distinctly clear water as compared to the lake. Most discharge points are marked by an algae overgrowth and bicarbonate salt precipitate. Most of the spring waters have a near neutral water (pH – 7.5) and a temperature ranging between 48-51°C.

5. Bolocho - Metincho hot springs located a few kilometers southwest of Chericha volcanic center a few hundred meters from Bilate River, the Bolocho group of springs have formed a number of pools which fill depressions on top of sinter and travertine cones which are up to about 5 m high from the surrounding plain with a base diameter of up to 200 m. The sinter and travertine cones indicate over flow from the pools was more vigorously in the past. Only three of the pools are now filled with hot water and only one of the pools have substantial discharge out of the cone. Two depressions on the northern most sinter and travertine cones do not contain water and have formed steam vents. All the hot spring discharges and pools have an alkaline water (pH 8-8.5) and range in temperature between 48 and 91°C with the deepest pool being filled with water of pH = 8 at 69°C. Metincho (meaning salt) springs which are located a

few kilometers south of the Bolocho group of hot springs and emerge from a base of a rhyolite dome overlain by conglomeratic and volcanoclastic lacustrine sediment. Discharge from numerous hotsprings joins to make a stream (≈200 l/s) which flows to nearby Bilate River. Most discharge points are surrounded by a swampy and algal overgrowth with a thin film of $NaHCO_3$ formed on the drier grounds. Temperature of the springs ranges between 45°C and 55°C and a pH of 7.5.

6. Bilbo active fumarolic and fossil hotsprings are located on the southern flanks of the Duguna Fango volcanic complex on the Bedesa - Dimtu road. The Anka Bilbo fumaroles are situated along the Wadu stream, where hot ground and weak fumarolic vents with a temperature as high as 89°C emerge from a country rock consisting of rhyolitic glass. Deep rooted hydrothermal alteration is spread out over an oval shaped area with about 600 m^2 diameter, with predominantly brick red 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 have formed condensates with no appreciable out flow from the small and shallow pools formed. Hydrothermal alteration along the fault scarp is brick-red and yellowish clay around the vents and minor travertine and sinter deposition which indicated that those vents used to be sites of near boiling alkaline chloride springs. A few hundred meters down slope from these 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.

7. Tobacco Plantation hot springs emerge from within a vesicular basalt flow unit (Qb_1) which makes the Bilate River bed. Numerous discharge point were identified on a site east of the river with some forming pools and a large discharge which forms a stream (≈300 l/s) 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 was being pumped for a 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 hydrothermal alteration and mineralization at these features.

8. Dimtu warm springs consist of numerous large discharge warm springs with temperature ranging between 38°C and 40°C and a near neutral pH. The springs emerge from the sand bedded gullies (up to 5 m deep) formed within the lake sediments, and collectively form a stream (≈300 l/s) which drains into Bilate River. Hydrothermal alteration is minor and is represented by a thin film bicarbonate salts on the lacustrine sediments.

Other localities of hydrothermal manifestation found in the area north and northwest of the Duguna Fango volcanic complex include the warm springs along the banks of the river Chereka and its tributary Busha which also represent a high discharge low temperature group of warm springs (32-35°C) related to Duguna Fango. The Boroa springs on the flank 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 and 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 (≈300 l/s) which drains into Bilate. The Boroa springs discharge water at a temperature between 43-45°C with near neutral pH. Hydrothermal mineralization at the surface is represented by a thin film of bicarbonate salt deposition over the country rock. About ten kilometers north of the study area near the base of Duguna Fango volcanic complex and the meandering Bilate River are found three phreatic (phreatomagmatic?) explosive craters. The three craters (Mechefera, Tido and Budimeda filled with warm saline water) are expressions and relicts of the most violent hydrothermal phenomena in the vicinity of the study area.

4. FLUID GEOCHEMISTRY

The proximity of the hydrothermal fields to the Quaternary rhyolitic central volcanic complexes and inferred ground water flow pattern in the region suggests that the Northwest Abaya Fault hot springs and fumaroles, are related to the larger Obicha complex rhyolitic center or the SalwaDore – Hako centers. Gross fluid geochemical features of these group of manifestations suggests structural conditions has allowed deep reservoir alkali-chloride waters to discharge with evidence for subsurface boiling a few hundred meters north of the lake to explain the nearby occurrence of acid sulphate springs and fumaroles. The Donga and East Abaya Fault hot springs appear to be related to either of the Donga, Kilisa or Werencha volcanic centers, where as the Bolocho - Metincho hot springs are most likely related to Chericha volcanic center. The Bilbo active fumarolic areas, Tobacco Plantation hot springs and Dimtu warm springs are related to the Duguna Fango volcanic complex. Geochemical data on hot springs (T > 65°C) from the study area (UNDP, 1973) enables to group the waters in to two generic types. The northwest Abaya group of hotsprings (#6, #8) show distinctly higher Cl/HCO3 and Cl/SO4 ratios as compared to the Bolocho and tobacco plantation group of hot springs even though Na/K for the former is lower indicating higher subsurface temperature. Furthermore the distinct Cl/B ratio from available hotspring analyses from the two groups suggests that the hot springs to the east and west of the Bilate river – Lake Abaya divide are tapping different reservoirs.

The northwestern Abaya near boiling hotspring (#6) with high discharge and siliceous sinter deposits is an alkaline chloride spring with the highest SiO_2 content (204 ppm) in the Lakes district. Inferred reservoir temperature from this spring which presumably has undergone the least mixing gave quartz equilibrium temperatures of 177°C and a Na/K ratio geothermometer temperature in the order of 265°C (UNDP,1973). The most vigorous fumarole in the Lakes District is located on the northwestern shore of Lake Abaya gave calculated equilibration temperatures based on H_2/CH_4 ratio – T-CH_4 = 169°C which is in reasonable agreement with quartz equilibrium temperature for spring #6 (Glover, 1976). Isotopic study on the spring discharges from the study area show relatively homogeneous compositions with (δO^{18}, δD) value showing a source on the mean precipitation line and quite distinct from the local surface water (Hamesa and Bilate Rivers) which lie on the evaporation enrichment line (fig 14, Craig, 1977) with only spring #6 showing a well defined oxygen shift (2.3 permill) thus providing an isotopic evidence for a high temperature subsurface water rock interaction.

5. HYDROTHERMAL ALTERATION

Hydrothermal alteration is found over a wider area around the active hydrothermal manifestations often controlled by tectonic features which indicates that the circulation of hydrothermal fluids had decreased in most cases in response to fluctuations of the regional peziometric level and / or self sealing of the hot water conduits in aquifers. The hydrothermal alteration in the study area can be grouped into three major types

1. Alteration related to fumarole vents is commonly deep rooted and pervasively affects the country rock with wide spread exposed surfaces of kaolinized country rock and native mineral sublimates such as sulfur (e.g. Anka Bilbo)
2. 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 (Northwest Abaya and Bolocho hot springs).
3. 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 (Northern Lake Abaya).

All the three types of altered ground are found in the northwest Abaya Fault hydrothermal field. Hydrothermal alteration from fumarolic vents is exposed along the southern part of fault scarp in the vicinity of the boiling spring which has sinter deposits. In the vicinity of the northern most (Chewkare) group of springs conglomeratic travertine deposits several meters thick are exposed on the fault scarp from whose base springs are currently issuing. This shows that there used to be much more vigorous hot spring activity in the Chewkare graben. Along the margins of the swampy ground of northern Lake Abaya there exists a wide area of hot ground which is covered by bicarbonate salts representing the third type of hydrothermal alteration in the area. Besides the northern Lake Abaya deep rooted alteration related to fumarolic activity is found only around the Bilbo fumaroles south of the Duguna Fango volcanic complex. At Horea Bilbo this type of alteration is found associated with sinter and travertine deposits which indicate the presence of boiling springs in the vicinity in the past. The Bolocho hot spring locality with its sinter and travertine cone deposits shows evidence for a more vigorous hot spring activity in the past. Other hot spring areas do not have near boiling point hot springs probably due to subsurface mixing with cold ground water. Minor hydrothermal alteration is found around most of this low temperature / high discharge springs and is characterized by bicarbonate salt deposition around the vents.

6. CONCLUSIONS AND RECOMMENDATIONS

The northwestern Lake Abaya hydrothermal field shows high temperature hydrothermal alteration which also suggests a wider spread and vigorous hydrothermal activity in the past. Eventhough the likely heat sources (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 a different hydrothermal reservoirs. The Bilbo area related to the Duguna central volcanic complex and the Bolocho area related to the Chericha central volcanic complex are therefore recommended to be given second and third priority for a more detailed geoscientific study.

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