# GEOTHERMAL STUDY IN NORTHWEST LAKE ABAYA AREA (SOUTHERN ETHIOPIAN RIFT)

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Gezahegne Yirgu

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## ABSTRACT

Geothermal energy, the cheapest among the different sources of power, is thought to provide a solution for the rising demand of electricity in Ethiopia, because the Ethiopian Rift Valley and Afar area have been identified to have one of the greatest geothermal potential in the world. The NW Lake Abaya geothermal province, situated in the southern part of the Ethiopian Rift Valley near to its western margin, is one of the target areas singled out for detailed exploration purposes. The area is characterized by high heat flow indicated by the presence of a number of hot springs, fumaroles and a geyser.

The volcano-tectonic evolution which started in early Miocene, has been in progress throughout Plio-Pleistocene and Quaternary activity has been evidenced in the most active part of the Rift. The volcanic products, represented by basalts and rhyolitic products, vary from alkaline to mildly alkaline and the recent fissural basaltic volcanism shows a transitional nature. The final silicic products are represented by peralkaline rhyolites, probably commendites.

The hydrogeological evidence suggests that quite abundant amount of water is recharged from the surrounding highland areas in the north and NW into the reservoir system and that the hot springs are all of meteoric origin. Important circulation of water at depth is evidenced from isotopic data.

The chemical characteristics of the thermal manifestations suggest the presence of two groups of thermal waters with different geochemical histories. A high temperature reservoir is represented by the first group while different degrees of mixing and dilution of the original

hot water with a cold subsurface groundwater is thought to give rise to the second group of thermal springs.

Preliminary geoelectrical survey indicates the presence of two low-resistivity zones separated by a layer of higher resistivity. The deeper low-resistivity structure has been tentatively interpreted to represent the geothermal reservoir of this area.

All the available data show that the studied area has all the necessary characteristics for the existence of an exploitable geothermal field of high enthalpy. A hydrothermal system with an estimated temperature of 200°C is considered to exist at depth between 700 and 1300 m within an area of about 45 km$^2$ extending for about 8 km north of the NW Lake Abaya shore. This system, present in Tertiary ignimbrite-basalt series, is dominantly a hot water system. An effective cover formation is thought to be provided by an impermeable layer of some 200 m thick. It is considered that both the magmatic heat source and the groundwater circulation supplying the reservoir are of regional importance.

CONTENTS

| | | Page |
|---|---|---|
| | ABSTRACT | ii |
| | FIGURES | vii |
| | TABLES | viii |
| 1. | Introduction | 1 |
| | 1.1 Physiographic Outlines | 3 |
| | 1.2 Previous Work | 5 |
| | 1.3 Purpose of Present Study | 6 |
| | 1.4 Methods of Investigation | 6 |
| 2. | General Geological Setting | 8 |
| | 2.1 Geology of the NW Lake Abaya Area | 11 |
| | 2.1.1 Tectonics | 11 |
| | 2.1.2 Stratigraphy and Volcanology | 13 |
| | 2.1.2.1 Old Basalts and Rhyolites | 15 |
| | 2.1.2.2 Hobicha Rhyolitic Lavas | 16 |
| | 2.1.2.3 The Chokare Ignimbritic Formation | 16 |
| | 2.1.2.4 Pumice and Ash Deposits | 21 |
| | 2.1.2.5 Recent Basaltic Flows | 22 |
| | 2.1.2.6 Recent Rhyolitic Lava Domes | 24 |
| | 2.1.2.7 Recent Obsidians | 25 |
| | 2.1.2.8 Fluvio-Lacustrine Sediments | 27 |
| | 2.2 Petrological Observations | 28 |
| | 2.3 Hydrothermal Manifestations | 38 |
| 3. | Hydrogeology | 42 |
| | 3.1 Climatology | 42 |

3.1.1. Rainfall 42

3.1.2. Temperature 46

3.2. Evaporation and Evapotranspiration 48

3.3. Runoff 50

3.4. Permeability of the Rocks 51

3.5. Local Recharge 52

3.6. Regional Recharge 54

3.7. Implications from Isotopic Data 55

4. Geochemistry of Thermal Manifestations 60

4.1. Chemical Classification of Waters 60

4.2. Implications from Chemical Constituents 69

4.2.1. Chloride and Boron 69

4.2.2. Alkali Ratios 72

4.2.3. $Cl/(HCO_3 + CO_3)$ Ratio 74

4.2.4. Other Ratios 75

4.3. Chemical Geothermometers 75

4.3.1. Silica 75

4.3.2. Alkali Ratios 79

4.3.2.1. Na/K 79

4.3.2.2. Na-K-Ca 81

4.4. Isotope Geochemistry 84

4.5. Gas Chemistry 85

5. Geoelectrical Results 90

5.1. Horizontal Profiling 91

5.2. Dipole-Dipole Results 93

5.3. Vertical Electrical Sounding (VES) 93

5.4. Correlation of Electrostratigraphy with Geology 101

6. Preliminary Geothermal Model 105

6.1. Heat Source 105

6.2. The Reservoir 111

6.3. The Problem of the Cover 114

7. Conclusions and Recommendations 117

ACKNOWLEDGEMENTS 122

REFERENCES 123

FIGURES

| | | Page |
|---|---|---|
| 1. | Schematic representation of the volcanic and tectonic evolution in the southern Ethiopian Rift | 14 |
| 2. | Correlation of stratigraphic sections from different localities in the vicinity of Lake Abaya area | 20 |
| 3a. | Annual rainfall map | 44 |
| 3b. | Morpho-climatic zonation map | 44 |
| 4. | Deuterium-Oxygen 18 compositions | 56 |
| 5. | Langelies-Ludwig diagram | 65 |
| 6. | Diagrams showing comparison of major dissolved solids | 67 |
| 7. | Diamond-shaped diagram | 68 |
| 8. | Graph showing Cl/Temperature relation | 71 |
| 9. | Graph showing B/Na relation | 76 |
| 10. | Graph showing Na/Ca relation | 77 |
| 11. | Sclumburger apparent resistivity map | 92 |
| 12. (a-e) | Dipole-dipole pseudo-sections | 94-98 |
| 13. | Dipole-dipole resistivity map (1:50,000) | 99 |
| 14. | Apparent resistivity curve | 100 |
| 15. | Preliminary electrostratigraphy correlated with geology | 102 |
| 16. | Interpretation of the overall gravity over East Africa | 106 |

## TABLES

| | | Page |
|---|---|---|
| 1. | Petrographic characteristics of volcanic rocks | 29 |
| 2. | Average monthly rainfall | 45 |
| 3. | Average daily temperature | 47 |
| 4. | Estimated evaporation and evapotranspiration | 48 |
| 5. | Isotopic compositions (Deuterium and Oxygen 18) | 58 |
| 6. | He-3/He-4 ratios | 59 |
| 7. | Chemical analyses (Thermal springs) | 61 |
| 8. | Chemical analyses (Surface waters) | 63 |
| 9. | Cl/B ratios | 70 |
| 10. | Alkali ratios | 72 |
| 11. | $Cl/(HCO_3 + CO_3)$ ratios | 74 |
| 12. | Estimated silica temperatures | 79 |
| 13. | Estimated Na/K temperatures | 80 |
| 14. | Estimated Na-K-Ca temperatures | 82 |
| 15. | Comparisons of estimated temperatures | 83 |
| 16. | Gas analyses results | 85 |

## 1. Introduction

Geothermal energy as a major potential alternative energy source has recently become a very important target for the economic development of many countries primarily because of the worldwide oil crisis and because geothermal energy has been proved to be much more widespread than it was believed earlier. The successful development of geothermal fields all over the world has been an impetus to geothermal exploration elsewhere and especially in those countries like Ethiopia where the prospect is large that it is considered to have one of the greatest potentials in the world (Lavigne and Marinelli, 1971; Varet, 1978; Di Paola and Getahun Demissie, 1980, in press).

The utilization of geothermal energy is practically free from danger of human life and environmental pollution. It does not require neither massive construction, as in the case of hydroelectric power nor advanced technology, as in the case of nuclear energy. Doo Jung Jin (1977) mentions cost analysis reported by Kaufman (1970) whose report (using the standard evaluation procedure suggested by the U.S. Federal Power Commission) revealed that of various energy resources geothermal energy will be least in the total cost for the generation of electricity under favourable conditions, still inexpensive and competitive with others under less favourable conditions.

At present time interest is concentrated on geothermal fields that can produce steam and/or hot water for the generation of electric power. The preferred requirements are temperatures above 200°C existing within permeable zones of rock within two kilometres of the surface and local heat flow large enough to keep the aquifer at its boiling temperature inspite of production.

A geothermal energy is also used for space heating, agro-industrial activities (green houses, refrigeration, desalination, etc.), hydrotherapy, extraction of chemicals (both associated or not with the geothermal fluids) and for fresh water supply.

It has been observed that areas characterized by an anomalous thermal gradient and various forms of hydrothermal activity are expected to show anomalously high temperature at depth which might represent exploitable concentration of geothermal energy. Such concentrations if found at depths between ½ and 3 km can be of economic importance. Deeper sources would be costly to exploit and shallower ones have insufficient pressure to permit the high enthalpy desired.

In Ethiopia various areas within the Rift Valley and the Afar area have been identified to possess great potential sources for geothermal energy. One of these areas is the north west Lake Abaya region where the presence of surface indications emphasizes the existence of a major geothermal field. In addition, the area is found within that part of the main Ethiopian Rift where active tensional movements as well as sub-historical volcanic manifestations occur, therefore producing high heat flow anomalies, The aim of the present study is to give a preliminary evaluation of the geothermal possibilities of the NW Lake Abaya area.

## 1.1. Physiographic Outlines

The main Ethiopian Rift Valley is a low-lying region between the Western Plateau and the Southeast Plateau. Large topographic scarps upto 1500 m (as in the Gurage scarp, Di Paola, 1979) and even exceeding 3000 m (as in Northern Shoa, Zanettin et al., 1974) mark the margins of these upland-regions. The rift margins are not everywhere marked by quite evident normal faults. In the southern part of the structure they seem to be poorly faulted. Whether this physiographic feature is the result of the predominance of flexuring over faulting or it is the result of fault obscurance by widespread recent volcanic products (ignimbrites, ash flows, etc.) it is not yet fully understood due to the lack of sufficient structural data.

The area described here is located in southern Ethiopia immediately NNW of Lake Abaya. It lies within the Ethiopian Rift Valley near to its western margin and covers an area of about 200 $km^2$, therefore representing roughly the 20% of an area, as discussed later where intensive faulting and volcanic activity took place in very recent times. The geothermal exploration was concentrated in such NNW portion of Lake Abaya area because it appears to be the most promising one.

This area is accessible by a track which separates from the main Soddo-Abba Minch highway. The track passes through Abela village - in the western part of the area - towards the Abaya State Farm, dividing the area into nearly equal parts. The track continues northwards towards Bilate State Farm and Bilate Tobacco Monopoly Farm. Four-wheël drive is only limited in the direction towards the foot-hills of Hobicha and Hoko mountains northeast of Abela village (see map).

The topography gently slopes from Wolaita Soddo (2050 m a.s.l.) south and southeast towards the axis of the rift. The rift margin to the west is not bounded by major faults. At Humbo some 20 km NW of Abela village there are faults which have exposed older basalts.

Young and distinct tectonic structures start appear-ing near Abela village. From here eastwards upto the lake, one comes across a series of young faults which have produced small horst-graben structures.

The major rivers flowing in the vicinity of the studied area are Bilate to the east and Hamassa to the west. No stream except the tributary of Hamassa is present in the area of study.

The tectonic lake of Abaya makes the southern boundary of the investigated area. This lake has an area of about 1126 $km^2$ and a maximum depth of 31.1 m. A number of big rivers (Bilate, Gidabo, Hamassa) feed this lake from all directions. These rivers carry from the adjoining highlands a lot of sediments into the lake as evidenced by the suspended clay and silt in the lake water which has given it the peculiar reddish-brown colour.

1.2. Previous Work

The Ethiopian Institute of Geological Surveys (EIGS) of the Ministry of Mines, Energy and Water Resources has conducted general geological investigations in the Lakes District prior to 1970. The main contribution comes from a regional mapping conducted by Di Paola (1970) as part of a new geothermal research.

It was not until 1970 that a formal programme of geothermal investigation was done by United Nations Development Programme (UNDP), under the request of the Ethiopian Government, thus allowing a significant expansion of geothermal research. Following the recommendation of UN work, the EIGS selected many target areas one of which was the NW Lake Abaya area, for detailed study by all feasible geological, geochemical, geophysical and hydrogeological methods.

A great deal of study has progressed since then which has made the Rift Valley in general and the area around Lake Abaya in particular more interesting from the geothermal aspect.

A semi-detailed geological investigation has been carried out by Berhane et al. (1978) while geochemical work was conducted by Negussie (1980, unpublished) from the EIGS. Some data on hydrogeology of the Bilate River Basin has been collected by Jovanovic and Teklegiorgis (1974) and Geroom (1980, unpublished) of EIGS.

The various aspects of study in the region led to interesting and positive results and geophysical study was being conducted during the writing of this paper. Researchers interested in the geothermal aspect of the Rift have also involved themselves in studying this area. Among these are Glover (1976), and Craig (1977) who studied the geothermal problem from the geochemical aspect.

## 1.3. Purpose of the Present Study

The purpose of the present work is that of collecting and synthesize all the existing published and unpublished data, to give additional geologic informations as well as petrographic description of rock samples and to present a tentative geothermal model, in order to get a generalized picture of the geothermal possibilities of the NW Lake Abaya area even though, of course, much more detailed work should be done.

## 1.4. Methods of Investigation

To fulfill the objective of the present study the following procedure has been adopted:

1) Geology and volcanology which consisted in:
   a) collection of all available data;
   b) detailed photogeological interpretation at 1/25,000 scale and field work on the Salodere-Hoko silicic domes (see map);
   c) stratigraphy of the main fault bordering the Salodere graben to the west;

d) additional stratigraphic study along the Chokare fault;

e) evaluation of the degree of permeability of the main rock units;

f) petrographic description of the most common rock types of the area;

g) relations between hydrothermal mainifestations (both active and fossil) and structural lineaments.

2) Geochemistry consisting in the collection of all data concerning water and gas analysis performed either at the EIGS Chemical laboratory or abroad (Glover, 1976; Craig, 1977).

3) Hydrogeology consisting in the collection of all data available.

4) Geophysics consisting in the collection of thè electrical resistivity work performed by EIGS (Jihad, 1980).

5) Finally, specific literature dealing with theoretical works related to geothermal problems as well as studies conducted on productive geothermal fields in many countries has been utilized in the present work.

## 2. General Geological Setting

In Ethiopia three important tensional tectonic structures namely, the Red Sea, the Gulf of Aden and the East African Rift meet in central-southern Afar Depression. In this region a model of evolution from continental break-up to typical oceanic-floor spreading ridges has been proposed (Barberi et al., 1974), as a result of plate motions between Arabia, Nubia and Somalia. This has produced new oceanic crust along NNW-SSE and WNW-ESE directions therefore joining the southern part of the Red Sea to the western termination of the Gulf of Aden spreading ridges through the Afar depression. The Afar depression therefore constitutes part of the Red Sea - Gulf of Aden oceanic megastructure which represents the Arabia-Nubia and Arabia-Somalia diverging plates boundary.

The plate boundary between the Nubian and Somalian plates follows the main Ethiopian Rift (Mckenzie et al., 1970; Barberi; and Varet, 1977; Le Pichon and Franchteau, 1978). Comparatively small extension has occurred here as compared to the spreading in the Red Sea, Gulf of Aden and the Afar. The lack of oceanic spreading in the rifts of East Africa is thought to be the result of the compression of the African plate between the spreading Mid-Atlantic and Mid-Indian ocean ridges (McConnel, 1972).

According to Barberi and Varet (1977) the East African Rift is the site of continental lithosphere attenuation marked by normal faulting, open fissures and associated volcanism.

This rift system moreover, differs from the oceanic rifts of Gulf of Aden and Afar-Red Sea by the frequent development of huge central volcanoes almost exclusively made of pantelleritic and comenditic products and the abundance of salic alkaline and peralkaline products occurring as fissural eruptions.

The Ethiopian Rift is essentially a very large graben formed by tensional movements as a result of drifting of the Nubian and Somalian plates with a concomitant domal uplift. It extends for some 800 km with a width varying between 35 and 85 km. A great number of step-faults produces a total difference of altitude of more than 1500 m (Di Paola, 1972) between the top of the plateau and the floor of the rift. All these are normal faults which run for hundreds of km in a NNE-SSW or NE-SE directions. These faults whose visible downthrows can easily exceed 300 m are disposed en echelon along the axis of the rift. Actually, the presently active axis of the Ethiopian Rift Valley, also known as the Wonji Fault Belt (Mohr, 1962) is not a continuous fractured belt over its entire length of about 800 km from SSW (near the Kenya border) to NNE (Lake Abhe), but it results in a series of right en echelon displaced areas (one of which is the NW Lake Abaya area described in this paper) where very recent and closely spaced normal faults and gaping fissures occur together with important volumes of fissural basalts and related differentiation products of very recent age and even historical (Di Paola, 1976; Bisouard and Di Paola, 1977; Bigassi et al.; 1979). It has to be noted here that two other important areas (Butajira-Silti and Bishoftu) of Quaternary (upto sub-historical) fissural basaltic volcanism are found some 50 km to the west of the Wonji Fault Belt near to the western margin of the rift. Geological and magmatological evidences (Di Paola and Seife; 1979) suggest that the structural environment responsible for the genesis of these basaltic rocks must be quite different from that of the Wonji Fault Belt.

Rifting in Ethiopia is thought to have began in early Miocene (± 25 m.y.) on an uplifted arch. Crustal attenuation and volcanic activity were the main phenomena during most of Miocene (25-10 m.y.). Eventhough stages of rifting were synchronous in Afar and in the Ethiopian Rift, oceanic crust has not formed in the latter, as mentioned above.

However, acceleration of crustal attenuation process in the last few million years at the axis of the Ethiopian Rift has been inferred from magmatological data (Bisouard and Di Paola, 1977). Mohr et al. (1978) have measured in the Nazret area using geodimeter survey, motions which are perpendicular to the rift faults at rates upto 6 mm/year.

Kazmin and Seife (1978) have forwarded the idea that the Ethiopian Rift formed only some 15-14 m.y. ago and that the initial sagging in the Rift occurred only as gentle warping. This is, however, in contrast with a great quantity of geological and radiometric data and moreover available structural data do not support the warping hypothesis.

## 2.1. Geology of the NW Lake Abaya Area

### 2.1.1. Tectonics

From the study of the southern part of the Ethiopian Rift, Zanettin et al. (1979) give the following evolutive process. The formation of the proto-rift took place towards the end of Oligocene. This wide and shallow proto-rift was bounded to the west by the Chenca plateau, The appearance of the "Ganjuli rift" (Lake Abaya) inside the proto-rift is presumed to be in Lower Miocene times (21 m.y.). No suggestion is advanced about what happened between 21 and 11 m.y. ago. The next episode resulted in a lift-up which narrowed the rift, whose floor was later covered by plio-pleistocene silicic products followed by Quaternary alkali basalt eruptions. Finally the axis of the Ganjuli gráben was fractured by the activity of the Wonji Fault Belt and alkali basalts, rhyolitic pumice and obsidians were erupted.

In the southwest end of the western Escarpment, immediately NW of the studied area, the structural limit between plateau and rift is not characterized by major faulting but only defined by physiographic feature as already mentioned. As soon as the area of study is approached numerous NNE trending faults become a characteristic feature. These are normal faults mostly dipping at 80 to 85$^{o}$ occasionally vertical and with small displacements. Fault spacing is dense with 200-300 m average separation. Faults have such features that the displacement along a single fault decreases and another fault, displaced *en echelon*, takes over.

The swarm of faults have in general downthrows to the east but downthrows to the west are also common. These have produced small horsts and grabens (rift-in-rift structures) which are especially remarkable east of Abela village.

Some major faults have formed larger grabens. The "Chokare graben" which is about 3 km wide and 10 km long is bounded to the west by the "Chokare fault" which has a visible displacement of nearly 100 m. To the east the bounding fault is not as impressive but well above 30 m. Anyway it has to be noted that the presence of important fluvio-lacustrine deposits as well as younger volcanic products must considerably decrease the actual vertical displacement of many faults in this area. Other major faults with displacements between 30-40 m, have defined the so-called "Salodere-Hoko graben" where the most recent volcanic activity is evidenced. This graben is about 3.5 km wide and some 13 km long.

Tilting of blocks by about 3-4° towards the west is apparent from outcrops west of Chokare fault. No visible tilting has been observed in the Salodere-Hoko area.

All the faults within the studied area look extremely young as shown by some faults which have affected recent rhyolitic flows as well as recent basaltic scoria cones and flows. However this faulting activity predates the most recent rhyolitic activity which has given rise to the Hoko and Salodere lava domes; these are not affected by any faulting phenomena but their activity must have been determined by the same mechanism of tensional movement: opening of fractures through which magma has escaped to the surface.

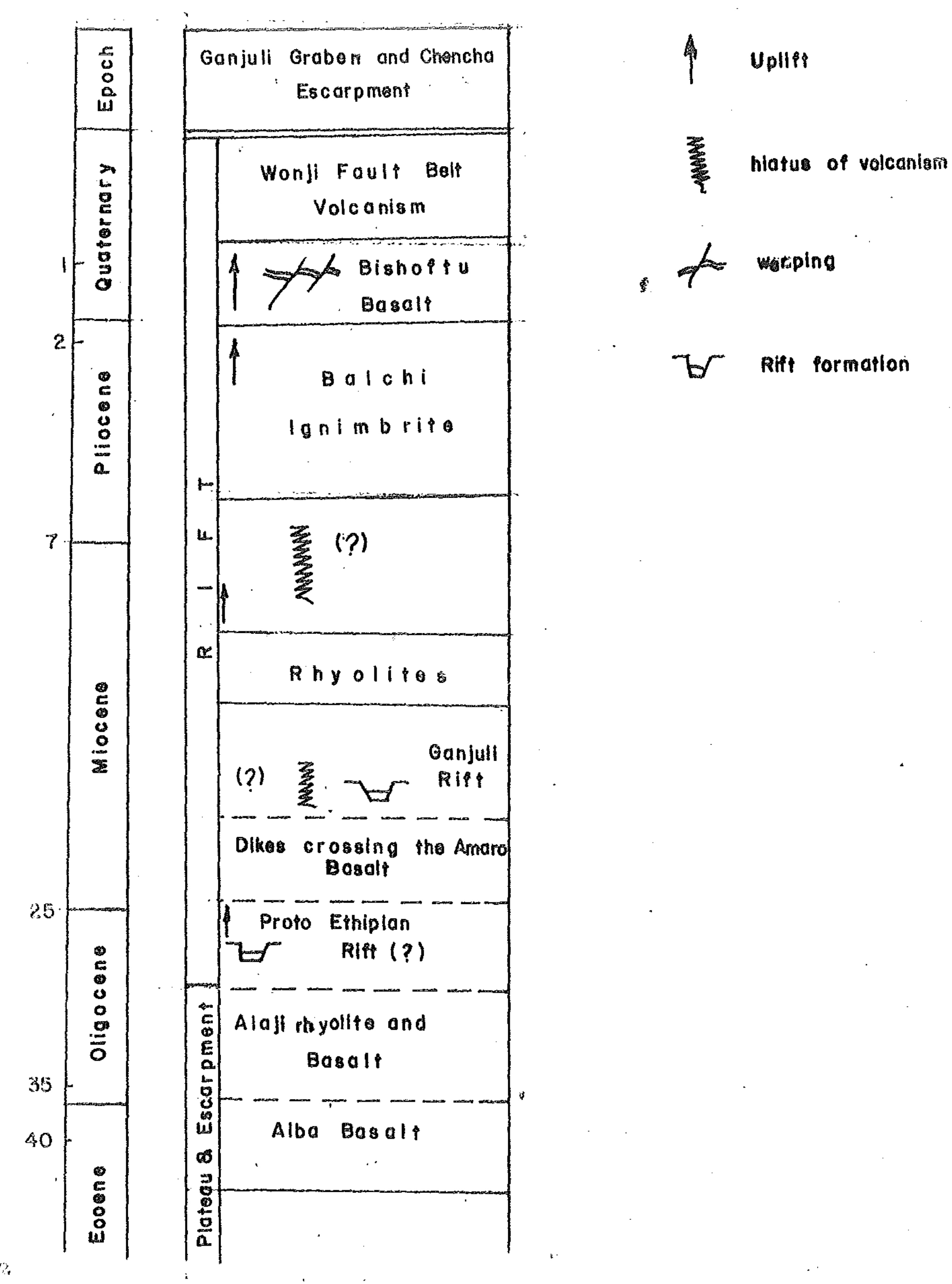
2.1.2. Stratigraphy and Volcanology

The surveyed area is exclusively made up of volcanic products associated with recent fluvio-lacustrine sediments. Rhyolites are the oldest outcropping rocks within the studied area and they are visible in the NW portion only. However, outside the studied area, to the east, older basalts have been observed to underlie ignimbrites (Berhane et al., 1978) (Ignimbrites make the lowest stratigraphic position at Chokare fault ). Whether the ignimbrites quoted are chronologically equivalent to those found in the studied area or not it is not yet clear because of the lack of sufficient data.

Zanettin et al. (1978) report that at the Chencha Escarpment which makes the western highlands, fine grained flood basalts (age 31.7 m.y.) are overlain by thick flows of massive white rhyolites (age: 11.9-13.3 m.y.) Their stratigraphy (Fig. 1) shows that after a volcanic hiatus Balchi ignimbrites (Pliocene) were erupted.

In the Humbo area, some 20 km NW of Abela village, it has been observed that old basaltic rocks underlie an ignimbritic formation which outcrops extensively

Fig.1. Schematic Representation of the Volcanic and Tectonic Evolution (After Zanettin et al., 1978)



upto Soddo and beyond.

In the NW Lake Abaya area, the stratigraphic succession has been constructed as follows:

| | |
|---|---|
| - alluvium and fluvio-lacustrine sediments<br>- recent rhyolitic pumice, ashes and obsidians<br>- recent basaltic spatter cones<br>- rhyolitic lava domes<br>- basaltic lava flows<br>- pumiceous pyroclastics<br>- ignimbritic formation<br>- Hobicha rhyolites | Pleistocene to Holocene |
| - old basalts (and rhyolites) | Oligo-Miocene according to Zanettin et al. (1978) |

2.1.2.1. Old Basalts and Rhyolites

These rocks do not outcrop in the studied area. As mentioned above, at the western margin (Chencha and Humbo areas), old basaltic and rhyolitic rocks are known to outcrop. In the vicinity of the Hamassa bridge on the Soddo-Arba Minch road, north of Wajufo Farm, a NNE trending fault has exposed the base of an ignimbritic formation. This formation is underlain by an older rhyolitic flow of unknown thickness. The ignimbrites are again overlain by pumiceous sediments which in turn are covered by recent basaltic flows. The stratigraphy here resembles that of Chokare except that no one-to-one correlation of the ignimbrite units is possible. Here the ignimbrites are of much lesser thickness.

2.1.2.2. Hobicha Rhyolitic Lavas

The Hobicha centre, in the NW corner of the studied area, has given rise to compact porphyritic rhyolitic lavas. The thick viscous flows have produced a prominent topography which overlooks most of Abela area. It is considered that the Hobicha rhyolite centre, which has an arcuate pattern, is the remanent wall of a volcano-tectonic collapse (Berhane et al., 1978). The Hobicha flows are the oldest rocks outcropping within the studied area, in fact a sample from the caldera wall has given a radiometric age of 1.57 m.y. (Berhane et al., 1978) at present the caldera wall appears moderately affected by tectonic activity.

2.1.2.3. The Chokare Ignimbritic Formation

Different authors have shown that ignimbritic outcrops form the oldest known rocks on the floor of the rift. Di Paola (1972a,1972b)states that ignimbrites are the most ancient outcropping formations at least south of the Addis Ababa latitude. In the Nazret Map Sheet, a thick succession of ignimbrites, unwelded tuffs, ash flows, rhyolites and trachytes (called the Nazret Group) form the larger part of the Rift floor (Kazmin and Seife, 1978). This formation is found all over the Rift extending from the eastern to the western escarpment.

In the studied area, ignimbrites outcrop only in the NW shore of Lake Abaya. This formation is made up of three units. The lowest ignimbrite unit at Chokare fault is a massive crystal-rich, greenish-grey variety. No fiamme are macroscopically visible. Outcrops are limited to a small area.

Overlying this is a purplish variety. This is also massive and crystal-rich containing xenocrysts of reddish and grey rhyolitic and basaltic fragments. Again no fiamme are visible macroscopically. An average thickness of about 30 m has been estimated for this unit.

Next in the succession comes a greyish-black unit which shows typical fiamme which appear vesiculated in the upper part of the unit while they appear compact near the base. Also in this unit xenoliths are quite abundant. This unit grades upwards into a dark brown tuff. The uppermost part is constituted totally of poorly consolidated ash and pumice. There is no clear separation between this unit and the overlying unit of pumiceous deposits. A visible thickness of 35 m has been measured for this uppermost ignimbrite unit.

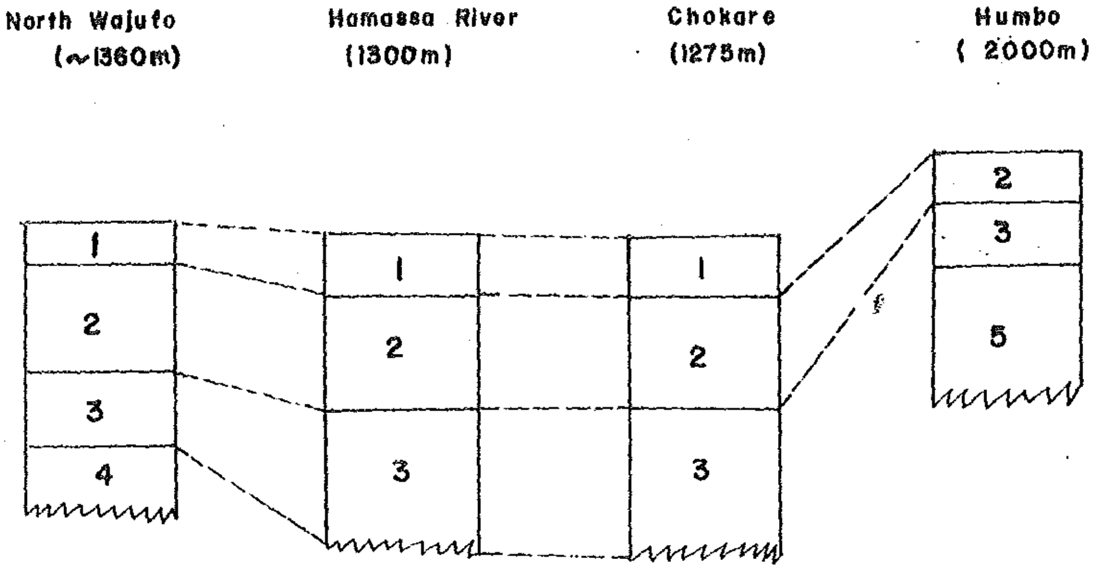
Fractures are present in this ignimbrite formation but no clear jointing has been observed. A slight tilting of about 3-4° to the west is indicated. The different units do not have uniform thicknesses. No outcrops of ignimbrite are found along the Chokare fault about 2 km NE of the hot springs. This is probably the result of wedging out of the formation northwards. It cannot be attributed to the amount of throw of the Chokare fault since here too, the throw is of the same order of magnitude.

An ignimbritic formation of the same nature outcrops in the Hamassa River Valley, just downstream from the main bridge on the Soddo-Arba Minch road (outside the mapped area). The lowest unit here is a brownish massive one which becomes greenish at the lowestmost outcropping part. What underlies it is not known. Overlying it comes a greenish-grey variety showing some sort of regular pseudo-layering. It contains some xenocrysts. The uppermost unit is separated by a thin layer (about 8 m) of yellowish material made up of well-consolidated ash and pumice. Next comes a greenish-brown unit which is overlain by yellowish pumiceous deposit. The topomost cover is made up of recent basaltic flows.

There is no indication as to the extent of the ignimbritic formation especially north of Chokare area. Here recent basalts have a continuous cover and faults are not large enough to expose what is below. Comparison of ignimbritic sections at Chokare, Humassa River Valley and area north of Wajufo Farm indicates a possible thinning westwards since the latter two sections show smaller thicknesses (see Fig. 2).

No clear centres of eruption are identified for these ignimbrites but they could be related to a rather big silicic central volcano (Duguna) found just at the northern limit (about 35 km) of the NW Lake Abaya area. A fission track age of 0.4 m.y. has been obtained from one of the most recent obsidian flows of Duguna (Bigassi et al., 1979). This fits very well with a K-Ar age of 0.87 m.y. found for the lower ignimbrite unit along the Chokare fault. It seems therefore that the ignimbrites of the studied area cannot fit in the general stratigraphy suggested by Zanettin et al. (1978) but they most probably belong to the Quaternary Dino ignimbrites of Kazmin and Seife (1978). It cannot be excluded, therefore, that below the ignimbrites exposed along the Chokare fault there could be important thicknesses of similar rocks but of older ages (probably the Pliocene Balchi ignimbrites of Zanettin et al., 1978). In this case the "old basalts and rhyolites" of Miocene age should be found at a greater depth than that expected when adopting the stratigraphy of Zanettin et al. (1978).

Fig.2 - Correlation of Stratigraphic Sections at Different Localities in the vicinity of NW Lake Abaya Area (not to scale)




| 1 | . Young basaltic flows, Pleistocene – Holocene? |
| 2 | Pumice and ash layers, Pleistocene |
| 3 | Ignimbrites (with interbeds of pumice), Plio – Pleistocene |
| 4 | Rhyolitic flow, Miocene? |
| 5 | Old basaltic flows, Oligo – Miocene? |

Except for the ignimbrites outcropping just on the NW shore of Lake Abaya as already described, no other outcrops of these rocks are found east of the Hamassa River near Abela village. They on the contrary extensively outcrop outside the studied area to the NW and in the Humbo-Soddo area. The stratigraphic correlation between the ignimbrites found within and outside the studied area is not clear.

2.1.2.4. Pumice and Ash Deposits

An important formation in this area is composed of several layers of what might be called pumiceous deposits, previously called "volcano-sediments" by Berhane et al. (1978). The unit is dominantly composed of pumice and volcanic ash with minute amounts of rock fragments. At Chokare, the unit attains a thickness of more than 35 m. Berhane et al. (1978) report that at places in the Abaya and Awasa areas (outside the studied area) similar formations contain interbeds of siltstones, claystones and sandstones.

Detail observation at Chokare outcrop at the road cut, shows that the unit is composed of several distinct layers. The lowest layer is about 12 m thick and is almost totally composed of coarse unwelded pumice which sometimes measures to 3 cm in size. Overlying this is a layer of agglomerate of pumice and ash with rhyolite and basalt fragments. A thickness of about 8 m is observed here.

Next comes a 4-m thick layer of massive reddish ash containing minor amounts of pumice fragments. Overlying it is a thin layer (1½ m) of poorly aggregated ash with some pisolitic fragments. The topmost layer consists of poorly sorted unwelded pumice fragments only. A thickness of more than 2 m is apparent. This observed layering does not continue laterally in a uniform manner. In fact, at places ash layers dominate over pumice outcrops.

It has been observed that these pumice and ash layers show poor sorting,. graded bedding and rounding. The lack of abundant clastic material implies that these deposits were not laid down under deep water. They were probably accumulated in a very shallow water and minor reworking process probably played a role afterwards. It is possible that similar deposits outside the area studied might have been reworked and later deposited under deeper water.

2.1.2.5. Recent Basaltic Flows

These basalts directly overlie the pumice and ash deposits and cover a very large surface area. They are the result of fissural flows of low viscosity magma. The whole formation has been intensely affected by tensional tectonics.

At least two varieties of basalts have been identified. An aphyric, massive and hard one characterized the first eruptions at least in some parts of the studied area. The base of this formation is only exposed in the vicinity of Chokare where the thickness is about 20 m while in the vicinity of Hoko dome the visible thickness of basalts exceeds 30 m.

The second variety is vesicular in character. Feldspar phenocrysts are abundant and randomly distributed. They sometimes measure upto 2 cm in size. Large vesicles with irregular shapes on the surface of the flow are common features. This flow is separated from the underlying one by a 2-3 m layer of scoriaceous material at the western and eastern faults bounding the Salodere-Hoko graben. It has a thickness of about 10 m here.

The thickness of the basaltic formation decreases away from the Salodere-Hoko area both in the east and west directions.

The last activity of these basalts consists of scoriaceous products which includes bombs and lapilli. Scoria cones have been observed to underlie the next volcanic episode which is the eruption of rhyolitic lavas.

However, basaltic lavas and associated spatters which seem to be relatively younger than those described above are found in some places. Eventhough the latter ones are not distinguished to be separate, they differ in their degree of freshness and preservation. It is not, therefore, excluded that they may belong to a later episode of basaltic eruptions separated from the earlier ones. These flows and spatter cones mark the last episode of basaltic activity in the area.

### 3.2.6. Recent Rhyolitic Lava Domes

These rhyolitic outcrops are confined to three individual centres in the investigated area about 7 km NE of Abela village. They are found adjacent to the Hobicha caldera mentioned earlier and directly overlie the basaltic flows and spatter cones.

These rhyolitic domes show a rather evident alignment and are of fissural origin. Viscous lavas were erupted probably at different times of short intervals as indicated by the slight differences of the rocks thus formed.

The dome nearest to Hobica rhyolites is a greyish-pinkish variety with a lot of quartz and alkali feldspars, highly devitrified. The upper part of the dome shows evident banding and is less porphyritic. The most top part is found as an obsidian facies. This lava dome is affected by faults of NNE direction.

The rhyolitic rocks forming the Salodere and Hoko domes are greyish in color and porphyritic in character. The upper portions are made up of less porphyritic (phenocrysts of quartz and alkali feldspars) greyish and only poorly devitrified rhyolitic lava. Faint banding is also shown by these rocks, These rhyolitic domes lie within the Salodere-Hoko graben and only minor faulting activity has affected them.

About 3 km northwest of Abela village, just south of Hobicha, there is a small dome made up of porphyritic and banded rhyolite lava. Associated obsidian is also observed.

This dome is situated on the western limit where the basaltic lava field ends and no clear presence of recent faults is evidenced. This rhyolitic extrusion probably belongs to the same episode of rhyolitic activity as that in the Salodere-Hoko area.

#### 2.1.2.7. Recent Obsidians

The last products of volcanic activity in the studied area are represented by thick flows of obsidian and a few pumice and ash falls. The obsidians are found on the central vents of the rhyolitic domes discusssed above. The largest volume of extrusion is from Salodere (meaning "obsidian" in local language) where a conical dome has been built. The obsidian here is black and only slight amounts of phenocrysts are visible. Those from Hoko are less porphyritic. The front parts of these lavas are highly vesiculated.

The western part of Hoko dome is at places covered by layers of pumice and ash which were probably erupted just before the topmost obsidian. Three distinct layers have been observed, in a gully. The bottom layer, more than 2 m thick is made up of very coarse pumice fragments. A middle layer of fine black ash about ½ m thick has its upper part mixed with pumice fragments. The topmost layer is also ½ m thick and consists of only coarse pumice fragments which become coarser uphill. The pumice cover makes an area of about 1 $km^2$. A thin layer of less than 5 cm of pumice fall covers the basaltic field and spatter cones in some places in the neighbouring area. These pumice falls seem to have erupted from craters present between Salodere and Hoko centres (see map).

These obsidian flows and pumice falls, judging from field evidence, must have been erupted very recently (Holocene). The Salodere obsidian flow has occupied a recent narrow gully and may even be historical (Di Paola, personal discussion). These flows have not been affected by any faulting. Weak traces of fumarolic activity and hot ground are present on top of the Hoko dome.

It has been observed that obsidians mark the last volcanic activity in many parts of the Ethiopian Rift Valley (Di Paola, 1972a, 1972b, 1976; Bisouard and Di Paola, 1977; Zanettin et al., 1978). Relatively fresh obsidian lavas are known within the Wonji Fault Belt from the complex volcanic centres of Aluto, Fanta'Ale and Gadamsa (Gibson, 1969; Di Paola, 1976).

3.2.8. Fluvio-Lacustrine Sediments

These sediments constitute the only non-volcanic formation and are limited to an area immediately north of Lake Abaya shore.

These sediments consist of deposits left behind by Lake Abaya when it occupied a larger area and a higher level. The area bordering the Chokare hot springs is permanently water-logged partly due to continuous inflow of water from the surrounding springs. A small faulted block of the pumiceous formation above described is surrounded by this marshy land. The materials forming these sediments consist mainly of clay and silt.

During heavy rains, the Bilate River carries a considerable amount of sediments to Lake Abaya as a result of which a large delta has been built at the inlet of the river to the lake.

No detail laboratory study on these sediments has been conducted. However, they most probably are of fluvio-lacustrine origin.

## 2.2. Petrological Observations

In Table 1 are listed the main petrographic characteristics of the samples collected in the studied area. Owing to the difficulty of making a complete detailed geology within the area represented in the geological map, no systematic sampling has been done. Therefore, the few available samples (some of which represent the same flow sampled at different places and even more the complete lack of any chemical analysis of the volcanic rocks of the NW Lake Abaya area) are not sufficient to allow consistent petrological considerations. However, some brief observations, which may be utilized as a working hypothesis for detailed future work, can be made.

From Table 1 it is clear that all the examined rocks fall into two compositional groups:

1. Basalts

Except for their different degrees of porphyricity, the only significant difference that can be observed is the presence in samples $21C_2$ and "Humbo basalt" of a coloured and pleochroic augitic clinopyroxene which suggests an alkaline nature for this basaltic magma. On the contrary, the mineralogy of all the other basaltic samples suggests an olivine-tholeiite composition. Unfortunately, no clear stratigraphic correlations between the Humbo basalt and the more recent ones is at present available.

Table 1 . Petrographic Characteristics of the NW Lake Abaya Area Volcanic Rocks

| Sample No. and Location | Texture | Phenocrysts | Groundmass | Rock Type |
|---|---|---|---|---|
| Humbo, about 25 km outside the mapped area to the NW | Slightly Porphyritic microcrystalline | Labradorite Plag, olivine (almost completely cloritised) | Plag. microlites, coloured and pleo-chroic augitic Cpx and Fe-Ti oxides | Basaltic lava flow |
| $21C_2$ same locality as 21A: (Top) | Porphyritic microcrystalline | Labradoritic plag, olivine and Fe-Ti oxides | Plag. microlites, Coloured & pleochroic augitic Cpx, olivine and Fe-Ti oxides. | Basaltic lava flow |
| $21C_1$ same locality as 21A: (Topmost) | Porphyritic microcrystalline | Large labradoritic plag, Olivine and Fe-Ti oxides | Plag, microlites, augitic Cpx, olivine and Fe-Ti oxides | Basaltic lava flow |
| $21B_2$ same locality as 21A: (Middle) | Porphyritic microcrystalline | Large labradoritic (An 62) plag, olivine and Fe-Ti oxides | Plag. microlites, augitic Cpx, olivine and Fe-Ti oxides | Basaltic lava flow |

| Sample No. and Location | Texture | Phenocrysts | Groundmass | Rock Type |
|---|---|---|---|---|
| 21A western part of the major fault scarp bordering the Salodere-Hoko graben to the west : (Base) | Subaphyric microcrystalline | Few microphenocrysts of labradoritic plag, olivine and Fe-Ti oxides | Microlites of plag, augitic Cpx, Fe-Ti oxides and olivine | Basaltic lava flow |
| 27C same locality as 27A (Bottommost) | Porphyritic microcrystalline (vesicular) | Large labradoritic (An 60) plag, olivine, Fe-Ti oxides and rare augitic Cpx | Plag, microlites, augitic Cpx, olivine and Fe-Ti oxides mostly as fine dust | Basaltic lava flow |
| 27A southern part of main scarp bordering Salodere-Hoko graben to the west (Top) | Porphyritic microcrystalline | Labradoritic plag, olivine and Fe-Ti oxides | plag microlites, augitic, Cpx, olivine and Fe-Ti oxides | Basaltic lava flow |

Table 1 Cont'd........



| Sample No. and Location | Texture | Phenocrysts | Groundmass | Rock Type |
|---|---|---|---|---|
| 27 B same locality as 27A (Bottom) | Subaphric microcrystalline | Microphenocrysts of labradoritic plag, olivine and Fe-Ti oxides | Plag, microlites, augitic Cpx, olivine and abundant Fe-Ti oxides | Basaltic lava flow |
| 14 Southern part of Salodere-Hoko graben | Porphyritic microcrystalline (vesicular) | Large labradoritic plag., Iddingsitized olivine and Fe-Ti oxides | Plag, microlites augitic, Cpx, olivine and Fe-Ti oxides | Basaltic lava flow |
| 13 Salodere-Hoko graben, 3 km SW from Hoko dome | Porphyritic microcrystalline | Labradorite (An, 63) plag, Iddingsitized olivine and Fe-Ti oxides | Plag, microlites, augitic Cpx, olivine and fine grains of Fe-Ti oxides | Scoriaceous basaltic lava flow |
| 26 About 2 km east of Chokare hot springs | Porphyritic microcrystalline | Labradoritic (An 67) plag olivine, Fe-Ti oxides and very rare augitic Cpx | Plag microlites, augitic Cpx, olivine and minor Fe-Ti oxides | Basaltic lava flow |

Table 1 Cont'd....

| Sample No. and Location | Texture | Phenocrysts | Groundmass | Rock Type |
|---|---|---|---|---|
| 24 Top of Chokare fault | Porphyritic microcrystalline (vesicular) | Labradoritic plag, olivine and Fe-Ti oxides | Plag, microlites, augitic Cpx, olivine and Fe-Ti oxides mostly as fine dust | Basaltic lava flow |
| 22 About 1 km west of No. 24 | Aphyric microcrystalline | —————— | Plag, microlites, augitic Cpx, olivine and Fe-Ti oxides | Basaltic lava flow |
| Hamassa river bed some 5 km SW of the mapped area | Porphyritic eutaxitic | Alk. feldspar (anorthoclase) Fe-Ti oxides, rare apatite and zircon | Abundant glass mostly devitrified. Some xeno-liths of silicic volcanic rocks | Peralkaline rhyolitic ignimbrite |
| Same locality as Humbo | Porphyritic eutaxitic | Alk. feldspar (Anorthoclase) alk. amphibole (Fe-Hasting-site) and Fe-Ti oxides | Abundant glass partly devitrified xenoliths of silicic volcanic rocks | Peralkali rhyolitic ignimbrite |
| 25D same locality as 25 A (Bottom) | Porphritic eutaxitic | Large alk. feldspar (anortho-clase), alk. amphibole (Fe-Hastingsite) and Fe-Ti oxides | Abundant glass partly devitrified, Numerous xenoliths of silicic volcanic rocks | Peralkali rhyolitic ignimbrite |

Table 1 Cont'd......



| Sample No. and Location | Texture | Phenocrysts | Groundmass | Rock Type |
|---|---|---|---|---|
| 25C same locality as 25A (Middle) | Porphyritic eutaxitic | Large alk. feldspar (anorthoclase). Aegerineaugitic Cpx, under transformation into alk. amphibole. Fe-Ti oxides and apatite | Devitrified glass Some xenoliths of silicic and basaltic volcanic rocks | Peralkali rhyolitic ignimbrite |
| 25A Chokare fault (Top) | Porhyritic eutaxitic | Alk. feldspar (anorthoclase) aegerineaugitic Cpx, Fe-Ti oxides, apatite. Alk. amphibole (Fe-Hastingsite) rare fayalitic olivine | Fresh brown glass. Abundant xenoliths of silicic and basaltic volcanic rocks | Peralkali rhyolitic ignimbrite |
| 17 4 km NW outside the western limit of the mapped area along Hamassa River bed | Porphyritic eutaxitic | Alk. feldspar (anorthoclase) Alk. amphibole (Fe-Hastingsite) and quartz | Devitrified glass. Xenoliths of pantelleritic lavas | Peralkali rhyolitic ignimbrite |

| Sample No. and Location | Texture | Phenocrysts | Groundmass | Rock Type |
|---|---|---|---|---|
| 4 Southern rim of Hobicha caldera | Porphyritic devitrified | Large Alk. feldspar (anorthoclase). Aegerine-augitic Cpx Fayalitic olivine, Fe-Ti oxides and apatite | Alk. feldspar microlites and oxidized Cpx. Devitrified glass. Strongly oxidized and cut by some secondary veins of quartz | Peralkali Rhyolitic lava flow |
| 20A Between Salodere and Hoko domes | Slightly porphyritic devitrified | Alk. feldspar (anorthoclase) Alk. amphibole (Riebeckite) and quartz | Some microlites of alk. feldspar, acmitic Cpx, alk. amphiboles (Riebeckite and Berkevickite) and quartz grains in a completely devitrified glassy groundmass consisting of quartz-alk. feldspar intergrowth (sometimes showing a typical micrographic texture). | Peralkali rhyolitic lava |

Table 1 Cont'd....

| Sample No. and Location | Texture | Phenocrysts | Groundmass | Rock Type |
|---|---|---|---|---|
| 3 (western slope of the northern-most recent domes) | Porphyritic hylocrystalline | Large alkali-feldspar (anorthoclase) Aegerine-augitic Cpx Fayalitic olivine Iron-titanium oxides Apatite | Abundant alk. feldspar microlites and Cpx almost completely oxidized. Scarce oxide grains. Rare intenstitial glass mostly devitrified. Diffused oxidation | Peralkali rhyolitic lava |
| 6 Top part of Salodere dome | Porphyritic vitrophyric | Alk. feldspar (anorthoclase) Aegerine-augitic Cpx., Fayalitic Olivine, Rare Fe-Ti oxides and apatite | Some alk. feldspar microlites and rare Cpx. Abundant glass mostly under devitrification | Peralkali rhyolitic obsidian lava |
| RV 380 (western base of Salodere dome) | Porphyritic Vitrophyric | Alk. feldspar (anorthoclase) Aegerine-augitic Cpx Fayalitic olivine, Rare Fe-Ti oxides and apatite | Some alk. feldspar and Cpx. (aegerine-augite) microlites, Rare fayalitic olivine, oxides and zircon. Abundant fresh glass | Peralkali rhyolitic obsidian lava |

2. Peralkali Rhyolites

Lava flows and ignimbrites in the NW Lake Abaya area have a constant peralkali rhyolite composition. Silicic peralkaline rocks, as it is well known, characterize the Ethiopian Rift Valley all over its length. The mineralogy of the studied samples suggests a low value of the peralkalinity index. This is supported, especially for samples No. 6 and RV 380, by comparison with an identical type of rock, found in another active area of the Rift floor, the Tullu Moje area (Di Paola, 1976; Bisouard and Di Paola, 1977) whose chemical composition is that of a comendite with a very low peralkalinity index (Di Paola, unpublished data). It is probable, therefore, that all the studied silicic rocks are comendites with variable peralkalinity index. The only exception seems to be sample 20A whose mineralogy suggests a higher peralkalinity so that this sample should fall in the pantelleritic field or at the limit between comendites and pantellerites. However, no clear stratigraphic correlations between petrographically different silicic rocks are at present available in the area.

One of the most accepted mechanisms for the genesis of peralkaline silicic rocks is the fractional crystallization of a parental mildly alkaline (olivine-tholeiite) basaltic magma. In the Ethiopian Rift Valley and in the Afar depression of Ethiopia, complete differentiation series from transitional basaltic magmas to silicic peralkaline end members have been found (Barberi and Varet, 1970; Barberi et al., 1975 Bisouard and Di Paola, 1977; Brotzu et al., 1979). It has also been noted (Barberi et al., 1975). that the less alkaline is the parental olivine-tholeiite, the less peralkaline are the end members (comendites instead of pantellerites). It can be concluded, therefore, as a working hypothesis, that the NW Lake Abaya Quaternary volcanic activity may be the result of fractionation of a mildly alkaline olivine-tholeiite magma trapped at a relatively shallow depth. The absence of coeval intermediate terms between the existing basalts and peralkali rhyolites is most probably not real because, as already mentioned, a detailed geological mapping and a consequent systematic sampling is till lacking not only in the area described in this paper, but also in the entire area north of Lake Abaya affected by very recent volcanic and tectonic activity. The probable existance of intermediate terms in this area is also suggested by the presence in some of the studied basaltic samples, of Fe-Ti oxides phenocrysts, which may suggest that at least some of these rocks already represent derivative liquids. Another indication of crystal fractionation is also given by the presence, in many basaltic lava flows, of abundant megaplagioclase phenocrysts.

## 2.3 Hydrothermal Manifestations

The superficial evidence for the existence of geothermal fluids at depth is the presence of thermal springs, geysers, fumaroles, hot grounds, hydrothermal alterations, phreatic craters, etc. Their occurrence and physical character can give some indication of conditions at depth.

In the investigated area, there are a number of hot springs and associated deposits. A geyser and a strong fumarole are also present. These have been well described in the UNDP geothermal work (UN, 1973, pp. 60-61). Two localities of steam emanations have been identified. Some indications of fossil springs have been observed. The localities where the main manifestations in the region occur (see map) are:

1. NW Lake Abaya area (springs 6, 7, 8, 10, 15, 16, 19)
2. Salodere-Hoko area (steam vents and hot grounds)
3. Hamassa River Valley (spring 17)
4. Area along Bilate River (Prison Farm, Bilate Farm, Bolocho....)

Only the first two localities are found within the studied area.

Spring 6 is found in the southern portion of the investigated area bordering the shore of the lake. It is associated with a weak geyser activity which is released at about 2 m above the lake level suggesting that reservoir pressures may exceed hydrostatic. A powerful fumarole which can be identified as an uprising steam from distance, emerges from near the geyser.

There are other 4 major groups of springs represented by springs 8, 15, 16, 19 aligned along the Chokare fault at different intervals extending for some 4 km northeastwards from spring 6. This tectonic line is the only place in the mapped area where hot spring phenomena is exhibited. This is probably due to the fact that this area of discharge is at a lower elevation, relative to the surrounding areas, and therefore nearer to the groundwater. This makes it easier for the groundwater to be discharged upwards through the fault fracture.

Some weak fumaroles and hot grounds exist on top of Hoko rhyolitic dome. Whether this activity belongs to gas emanations of volcanic activity or to steam produced as a result of separation from hot groundwater is not known. However, some hydrothermal deposition has been observed suggesting emanations from underground hot water system.

Some 200 m north of the Salodere obsidian lava front, there are two spots where weak steam emanations occur. These spots seem to be aligned along an east-west line. The steam emanations, according to local people, were much stronger some 6-7 years back and that a low-discharge warm spring existed. Observation shows that a small gully has been produced at one of these spots indicating the presence of a hot spring in the past. There is no trace, however, of any hydrothermal alteration products.

There are widely distributed thermal springs in the vicinity of the studied area. A group of springs occur along Hamassa River bed (spring 17) some ½ km downstream from the main bridge along the Soddo-Arba Minch road.

Further east and northeast from Chokare, thermal springs exist along the Bilate River. These occur at Prison Farm, Bolocho, Bilate Farm and Bilate Tobacco Farm. Hot springs are common around Duguna peralkali rhyolitic centre some 35 km northeast of Lake Abaya. According to Berhane et al., (1978) the hot springs all along Bilate River are of low temperature, low discharge types without deposition of sinter. Those at Bolocho have deposited extensive amounts of calcareous sinter and are probably of deeper origin. These hot springs lie along a line with N15$^{o}$E trend suggesting the existence of an old fault zone along which they ascend to the surface.

The major alteration product of hydrothermal origin is travertine in the Chokare area where large areas (upto 500 $m^2$) are sometimes covered. Some fresh hydrothermal deposits are being formed from some of these hot springs. Siliceous sinter deposition has occurred in association with spring 6. The area around the geyser is a zone of oxidized products stained reddish-brown and a small quantity of hydrothermally deposited crust of sulphides also exists. A "frying-pan" type of hydrothermal activity is present associated with spring 7. Some hydrothermal deposition of what looks like siliceous sinter has also been observed associated with the weak fumarolic activity on top of Hoko rhyolitic dome.

Hydrothermal alteration products are found in many of the hot springs at higher elevations indicating that the springs used to occupy higher positions and had a much widespread

# 3. Hydrogeology

This hydrogeological work is intended to study in a generalized manner the recharge areas, to determine the relationship between permeable and impermeable layers and to study the characteristics of aquifers.

The main part of this work stems from information obtained from the works of Jovanovic and Teklegiorgis (1974), Raunet (1978) and material provided by Geroom (unpublished). Geochemical studies performed by UN (1973), Negussie (unpublished) and Craig (1977) have provided a lot of aid also.

## 3.1. Climatology

In this part on climatology only those features connected with hydrogeology are discussed. These include rainfall, temperature, evaporation and river flows within the basins of Bilate and Hamassa Rivers. Attention is given to aquifer recharge by rainfall and seepage. The area of interest is located in such a position between the basins of Bilate and Hamassa that only scanty information is available on the above features. As a result discussion has been possible only in a very generalized manner.

### 3.1.1. Rainfall

According to Raunet (1978), the rainy season varies with latitude and that north of parallel $6^{o}30'$ (roughly north of Lake Abaya) it is from July to September with a secondary peak between

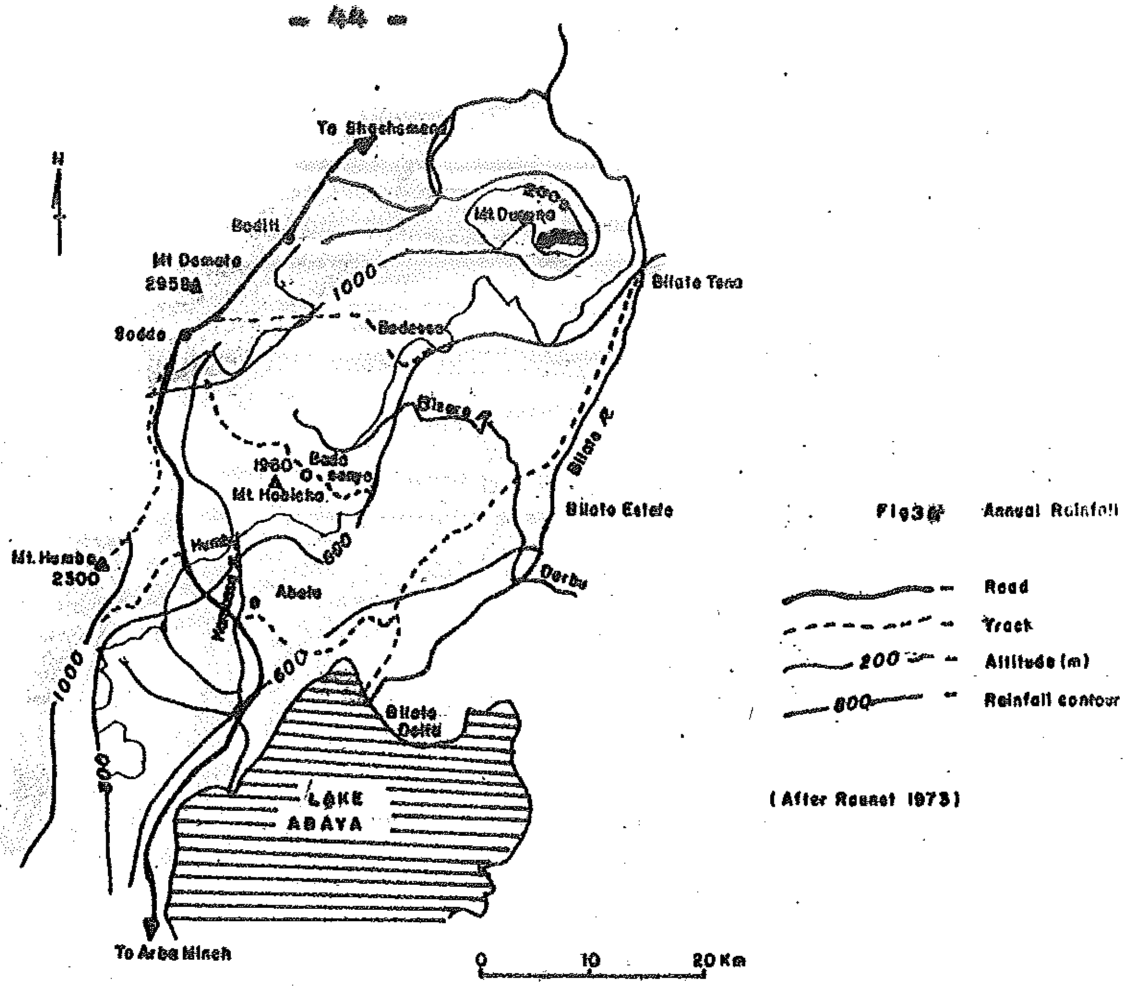



Fig 3a Annual Rainfall

(After Rounet 1973)

Fig 3b- Morpho climatic zonation
(After Rounet 1973)

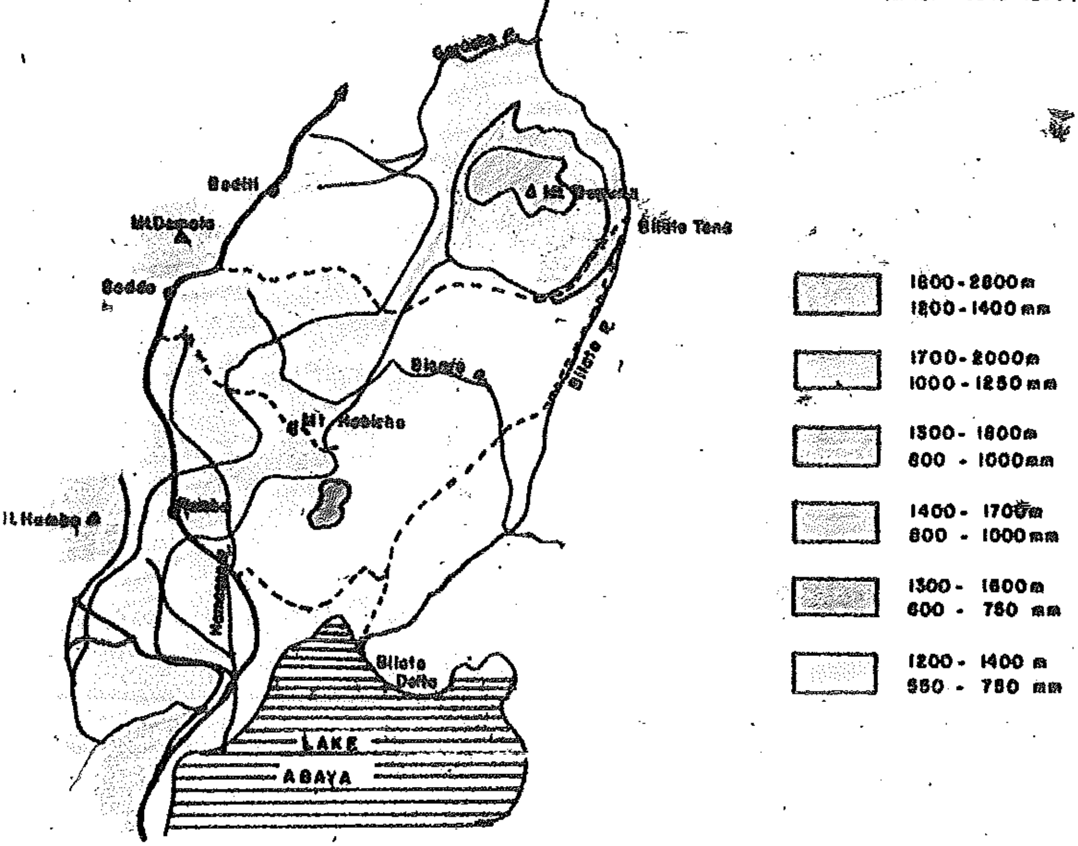


Table 2 . Average Monthly Rainfall. (Source: Jovanovic and Teklegiorgis (1974))

| Station | Attitude (m a.s.l.) | J | F | M | A | M | J | J | A | S | O | N | D | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Soddo 1954-1966 1971-1972 | 2050 | 22 | 47 | 94 | 166 | 162 | 161 | 277 | 171 | 113 | 116 | 59 | 34 | 1365 |
| Tena Bilate 1973 | 1500 | - | 3.2 | 0.0 | 59.7 | 90.7 | 112.8 | 293.6 | 62.8 | 114.7 | 72.5 | 13.4 | - | 800 |
| Bilate Farm 1970-1973 | 1340 | 40 | 45 | 15 | 100 | 75 | 75 | 70 | 75 | 80 | 50 | 30 | 28 | 683 |
| Abela 1971-72 | 1540 | 11.8 | 48.9 | 15.4 | 154.4 | 126.8 | 119.9 | 131.6 | 83.1 | 37.8 | 51.2 | 97.2 | 19.3 | 897.4 |

These figures are not so much reliable and great irregularity in both the distribution and annual total of rainfall is a characteristic feature of the region. In general it can be concluded that the region receives between 700 and 1380 mm of rain per year. Since the lower regions of the Rift floor represent the local cold water sink for the precipitation of the surrounding highlands, the movement of cold water towards Lake Abaya area is thought to be appreciable.

3.1.2. Temperature

A true picture of the temperature distribution cannot be presented but the trends have been observed to be as follows. According to Raunet (1978), the mean monthly minimum temperatures are lowest from October to January while the mean monthly maximum temperatures are highest from February to April. The annual means fall regularly as the altitude rises. In the Lake Abaya area the annual means vary between 21°-23°C while at an altitude of 2000 m they fall to 16°-18°C. At Bilate Farm, the lowest temperature is 20.8° in July and the highest is 24.3° in February. Only slight monthly variations are observed here while the daily variation is 8.9°C in July and 18.2°C in March.

Table 3 . Average Daily Temperature (°C) (Source: Jovanovic and Teklegiorgis (1974))

| Station | Year | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bilate | 1972 | 23.4 | 23.2 | 23.2 | 22.6 | 22.4 | 21.6 | 21.4 | 21.4 | 21.8 | 22.4 | 22.5 | 23.4 |
| Estate | 1973 | 24.0 | 25.0 | 25.4 | 24.8 | 23.4 | 22.4 | 20.8 | 20.8 | 22.0 | 21.6 | 22.2 | 22.1 |
| Abela | 1973 | 22.6 | 24.6 | 25.2 | - | 22.7 | 21.6 | 20.0 | 19.6 | 21.0 | 22.2 | 21.4 | 21.0 |
| Wolaita Soddo | 1970 | 17.8 | 19.4 | 18.0 | 18.0 | 17.2 | 15.8 | 15.0 | 14.4 | 15.6 | 15.8 | 17.0 | 16.8 |
| | 1971 | 17.4 | 19.0 | 19.8 | 17.9 | 17.6 | 15.4 | 13.6 | 13.8 | 14.1 | 14.3 | 14.8 | 14.3 |
| | 1972 | 15.7 | 16.2 | 16.8 | 16.4 | 16.2 | 14.6 | 13.4 | 13.9 | 14.3 | 14.8 | 14.4 | - |

The region which encompases Abaya Farm, Bilate Farm and Abela has the highest mean temperatures and a semi-arid environment prevails. Table 3 gives a general picture of the distribution of temperatures in some areas.

## 3.2. Evaporation and Evapotranspiration

The insufficient data do not allow the determination of evaporation and evapotranspiration in the region. Only estimates can be forwarded by comparison, in a very generalized manner, with other areas having similar climatic patterns. For instance, evaporation has been calculated for Zwai, Wonji and Metehara areas (UN 1973). The basin under consideration can be compared to have similar features and similar proportional evaporation and evapotranspiration figures have been estimated.

Table 4. Estimated Evaporation and Evapotranspiration Figures

| Station | Height (m) | Mean Annual Evaporation (mm) | Mean Annual Evapotranspiration (mm) |
|---|---|---|---|
| Addis Ababa | 2408 | 1407 | 737 |
| Zwai | 1625 | 2000 | 862 |
| Wonji | 1540 | 2227 | 855 |
| Metehara | 955 | 2946 | 983 |

Estimated Figures

| | | | |
|---|---|---|---|
| Soddo | 2050 | 1500 | 760 |
| Abela | 1540 | 2227 | 855 |
| Bilate Farm | 1340 | 2300 | 910 |
| Abaya Farm | 1280 | 2400 | 920 |
| [x] Awasa | 1760 | 1754 | |

[x](measured in 1973)* — *Jovanovic & Teklegiorgis (1974)

The estimated figures would be probably higher than the real values since mean temperatures in the studied area are not as high as in the areas compared and proximity to highland areas has a cooling effect therefore reducing evaporation and evapotranspiration. These comparisons simply show the trend in the change of evaporation and evapotranspiration. Depending upon the characteristics of a given locality, it is possible that the true values might vary by considerable degree.

It can be observed that an inverse relationship exists between evaporation and evapotranspiration on one hand and altitude on the other. Study in the Lower Awash Valley (UN 1973) shows that below altitudes of around 1700 m (same altitude of Zwai) potential evapotranspiration exceeds rainfall. A similar situation can be thought to exist in the Lower Bilate and Hamassa River Basins. Here the portions of the basins above 1700 m are thought to feed the streams while the rains occurring in the low-land regions are used for evaporation and evapotranspiration losses and only a small amount of water remains for infiltration. This assumption is not strictly justified due to the proximity to highlands and that in reality in these areas rainfall not only compensates the evaporation losses but considerable infiltration occurs.

## 3.3. Runoff

Runoff is determined by drainage density, relief characteristics and type of surface and rainfall. In the case of Bilate River the annual average runoff, from stream gauging records at Alaba Kolito has been measured to be $351.20 \times 10^6 m^3$ or $11.2 m^3$/sec. (Jovanovic and Tekle Giorgis, 1974). Most of this water results from precipitation and a small amount from spring discharges. No runoff data is available for Hamassa River. From the parameters which govern the runoff (mentioned above) Hamassa River has a much lower runoff as compared to Bilate.

Runoff is probably much higher on the ignimbrite outcrops which make the higher water courses of both Bilate and Hamassa Rivers. The tectonic features within the basalts as the Rift floor is approached probably aid rapid percolation and thus runoff on them is thought to be small.

## 3.4. Permeability of the Rocks

The different rock units outcropping in the NW Lake Abaya area possess variable permeabilities. Those rocks intensely fractured by tectonic activity are highly permeable. This applies to almost all outcropping rock units except those which are younger than the last tectonic activity and have not been faulted. However, no detail study on fracturation of rocks has been conducted. The loosely consolidated pumice and ash deposits definitely provide a highly permeable formation, at least in the area studied. Contacts of individual lava flows are believed to provide good permeability. All the recent volcanic formations in the rift have been considered to be strongly permeable by Di Paola (1970).

Volcanic rocks with variable permeability are governed by two contrasting processes: hydrothermal alteration and fracturing. Tuffs and lavas locally undergo an impermeabilization process as a result of hot fluid circulation (Tonani, 1970). Previous permeable areas may be sealed by this process depending upon the degree of alteration. This process must be decreasing the permeability of rocks at depth. Tectonic fracturing, on the other hand, is believed to have increased the permeability. The ignimbrites which have different characteristics with respect to grain shape and size, compaction and weathering possess variable permeability. These rocks vary from welded crystal-rich varieties containing compact glass fiamme to less compact and friable types containing a lot of ash and pumice. The primary permeability is affected to a great degree by tectonic fracturing as well as hydrothermal alteration at places. The net effect is that of increased permeability except where alteration is dominant.

The alluvium and fluivio-lacustrine sediments near the northern shore of Lake Abaya, form an impermeable layer. The rhyolitic domes poorly or not affected by fracture are considered impermeable. On the other hand, the most recent obsidians are compact and not faulted but are intensively cracked by cooling contraction. It is therefore, unlikely that they fall into the imperme- able class and are of less importance.

3.5. Local Recharge

If one looks at the estimated values of potential evaporation and evapotranspiration which are higher than mean annual rainfall figures no recharge is expected to occur in the lowlands of NW Lake Abaya area. The situation is probably much better and a small amount of local recharge is expected.

The shallow groundwater within the Bilate River Basin follows the ignimbritic topography (which outcrops extensively in the upper Bilate River Basin) and becomes deeper as the Rift floor is approached. A shallow groundwater ( 60 m depth) exists at Bilate Farm (Groom, unpublished). In the immediate vicinity of the area of study no cold springs have been encountered. However, there are signs of previously discharging springs of probable shallow origin immediately north of Salodere rhyolite dome where very weakly steaming ground is now present suggesting that local recharge must be rather significant.

A cold spring at Humbo, some 20 km NW of the studied area, is an alkaline-earth bicarbonate type (see later) which indicates that there is local recharge in the region since this type of water suggests limited interaction with rocks and limited time of residence.

Following the method employed by Aquater (1979) to estimate local recharge in the Tendaho area (southern Afar), the yield of the local recharge in the vicinity of the studied area can be estimated with certain assumptions. The surface of study area for local recharging comprises mainly of recent basalts and this area is estimated to be roughly 1000 $km^2$ including those areas further NE and SW. For the basalts an infiltration coefficient of 0.3 can be assumed. Using the yearly average precipitation of about 750 mm in the considered area, a local recharge is obtained as follows:

$$1000\ km^2 \times 750\ mm \times 0.3 = 2.25 \times 10^8\ m^3/year$$

This amount is quite significant, The value is a reasonable one since intense faulting facilitates the process of recharging. This estimation on the other hand, simply shows the trend in local recharge and does not actually represent the amount which infiltrates into the groundwater system since many other factors have not been accounted for.

## 3.6. Regional Recharge

The regional pattern of the groundwater flow in the Bilate River Basin is considered to be from north to south as well as from west to east towards Lake Abaya (Geroom, unpublished). As exceptions, local basins might have their own pattern of water circulation. Thus regional recharge in the NW Lake Abaya area comes from different sources. These include deep recharge from the north, west and northwest mainly by infiltration of rainfall. Seepage recharge from Bilate and Hamassa Rivers and their tributaries along their courses contribute a small amount. A deep recharge from the east and northeast highland areas (within the Bilate River watershed) must come towards the topographic sink of the rift lowlands and finally towards Lake Abaya area.

A large amount of water will recharge the deep aquifer that outcrops as older formations in the north and northwest highland areas and thought to continue at depth in the studied area. The amount of this regional recharge cannot be determined from the available data but it is thought to be rather considerable partly because rainfall in the highland areas is high.

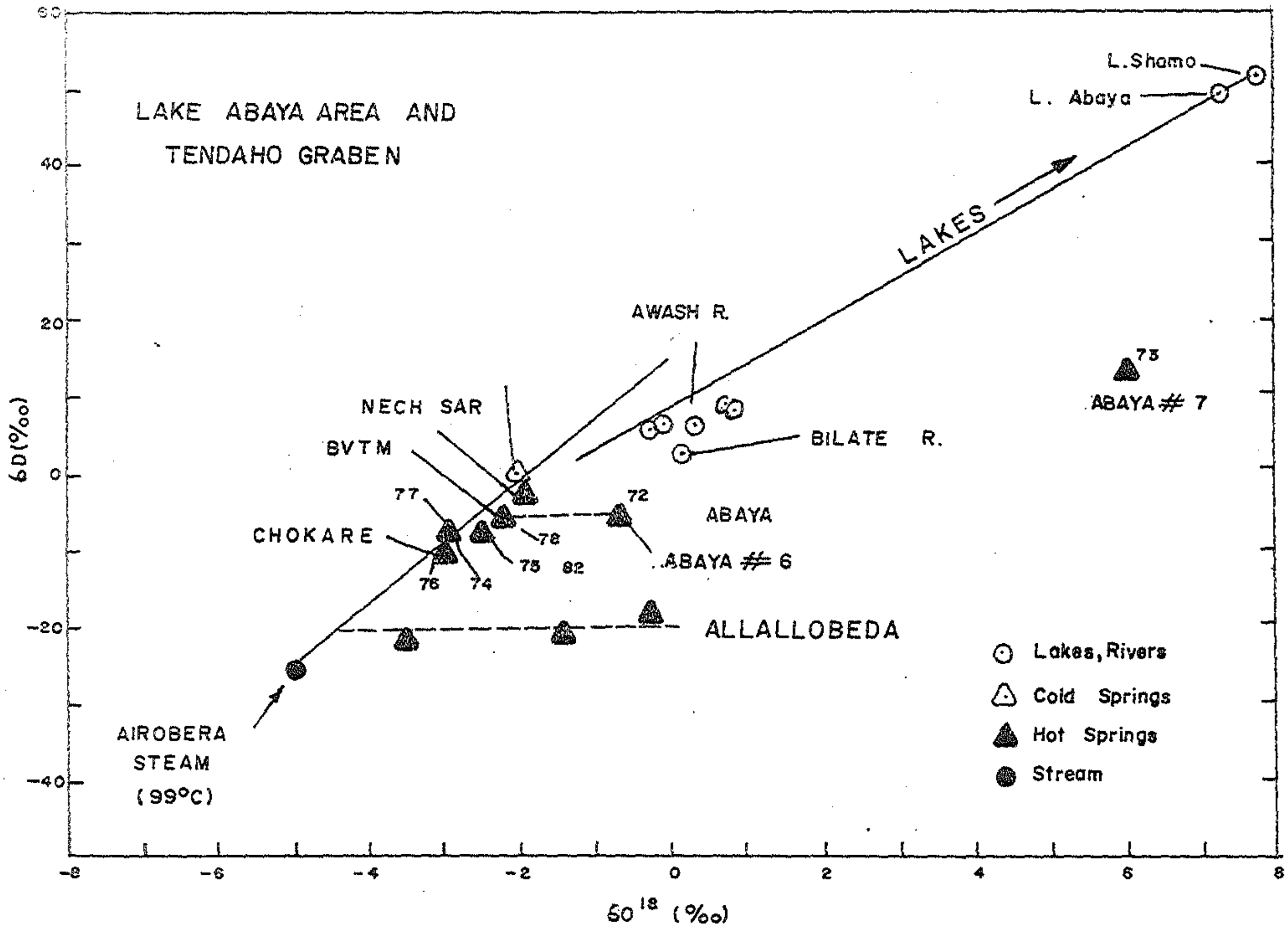
A tentative hydrogeologic scheme can be imagined where Lake Abaya is the locus of convergence of ground-water flows from several directions the main features of which have been discussed above. Of great importance is the considerable regional recharge from the adjoining highland areas and seepage through fault fractures.

Underground waters circulating at depth emerge along fault zones at least in the NW Lake Abaya area. The groundwater system seems to be rather extensive as evidenced by the distribution of thermal springs through-out the region north of Lake Abaya.

## 3.7. Implications from Isotopic Data

The results of measurements of the isotopes of deuterium, O-18, He-3 and He-4, and C-13 for the waters of the Rift Valley have already been described by Craig (1977). The following summarized account stems from this study.

The deuterium and O-18 results are summarized in Table 5 and Fig. 4 . According to Craig (1977) the Abaya and Bilate Farm thermal waters form a relatively homogeneous group with an identical source composition on the mean precipitation line at delta values of O-18 and D of -3, -9 respectively. This source water is quite distinct from the local surface drainage - the




Sample Designations

| Craig(1977) | | UN(1973) |
|---|---|---|
| 72 | = | 6 |
| 73 | = | 7 |
| 74 | = | 8 |
| 76 | = | 15 |
| 77 | = | 16 |
| 82 | = | 13 |

78 = BVTM = Bilate Virginia Tobacco Monopoly Springs.

Fig. 4 - Deutrium — O — 18 Compositions
After Craig(1976)

Bilate and the Hamassa Rivers both of which lie on the evaporation-enrichment line at O-18 values of about zero. The enriched isotopic compositions of these rivers is explained to be due to evaporative effects either in falling precipitation during the dry season or on the ground. The isotopic enrichment of Bilate River in the upstream part with respect to the downstream part indicates input of relatively unevaporated water in the middle course. This unevaporated water must be provided by rivers like Garache and Bisare (Fig. 3 ) which originate from Mt. Damota area and join the Bilate in its middle course.

The isotopic data indicate that the thermal waters discharged from the NW Lake Abaya area as well as those from Bilate area are of meteoric origin which originated from precipitation on the highlands to the north and northwest. The data also reflect that a large evaporative loss with respect to precipitation and inflow occurs in Lake Abaya (delta D = 49.6, delta O-18 = 7.25). It can be observed that the hot springs in the surrounding area have quite different stable isotopic compositions. It is, therefore, concluded that none of the hot springs in the NW Lake Abaya area receive a major contribution of water from this lake.

Table 5. Isotopic Composition of Hot Springs and other Waters in Lake Abaya Area

(Source: Craig, 1977, p. 67)

| Sample Designation | D/H | O-18 |
|---|---|---|
| 6 | -5.7 | -0.66 |
| 7 | 13.3 | 6.06 |
| 8 | -8.7 | -2.88 |
| 10 | -7.8 | -2.48 |
| 15 | -9.4 | -2.98 |
| 16 | -7.1 | -2.90 |
| 17 | -7.3 | -2.48 |
| Bilate River near L. Abaya | 2.2 | 0.14 |
| Bilate River at Alaba Kolite | 8.0 | 0.85 |
| Bilate Tobacco Farm Springs | -5.7 | -2.17 |
| Hamassa River | 6.2 | -0.07 |
| Lake Abaya | 49.6 | 7.25 |

Information concerning the aquifers feeding the hot springs around NW Lake Abaya is available from studies of He-3 and He-4 ratio measurements. These ratios (Table 6 ) show that the NW Abaya springs give values of $R/R_A$ = 4.0 - 7.2 ($R/R_A$ is the corrected He isotope i.e. the non-atmospheric part). This has been interpreted (Craig, 1977) as evidence for similar geochemical histories or even for connection to the same aquifer. However, the results are not so tightly grouped as to suggest a common source for all the springs

(as, for instance a value of $R/R_A = 3.0 \pm 0.2$ found in Geyser Island and Bole around Lake Langano.)

The relatively low ratios of He-3 and He-4 which have a direct association with relatively recent basalts, confirm the result from geology that the deep aquifer does not have any association with recent basalts but instead with relatively older formations. The low values also exclude the possibility of a direct connection of the aquifer with a magmatic source immediately underneath which usually give high He enrichments.

Table 6. He-3, He-4 Concentrations

(Source: Craig, 1977, p.95).

| Sample Designation | Fluid Phase | | | Gas Phase | | |
|---|---|---|---|---|---|---|
| | Helium | | $R/R_A$ | Helium | | $R/R_A$ |
| | $\mu$cc/g | $\mu$cc/g / 0.0455 | | ppm | ppm/5.24 | |
| 6 | 0.02 | 0.4 | 3.3 | - | - | - |
| 7 | - | - | - | 0.2 | 0.04 | 4.0 |
| 10 | 0.013 | 0.3 | 3.2 | 0.95 | 0.2 | 6.8 |
| 15 | 0.24 | 5.3 | 6.8 | 37.1 | 7.1 | 7.2 |
| 15 (NC)[⊗] | - | - | - | ✝ | - | 7.3 |
| BVTM[+] | 2.0 | 44 | 8.1 | - | - | - |
| Air saturated water (15°C) | .0455 | 1.0 | 1.0 | - | - | - |
| Air | - | - | - | 5.24 | 1.0 | 1.0 |

\+ - BVTM = Bilate Virginia Tobacco Monopoly hot springs

NC[⊗] = non-condensible gas only ($CO_2$ removed)

✝ = Helium in non-condensible gas phase = 1175 ppm

1 $\mu$/g = $10^{-6}$ cc STP Helium per gram of water

Freshwater in equilibrium with air at 15°C and 1 atmosphere air pressure has Helium concentration of 0.0455 /g.

$R = He\,3/He^4$, $R_A = (He\,3/He^4)_{Air} = 1.4 \times 10^{-6}$

# 4. Geochemistry of Thermal Manifestations

## 4.1. Chemical Classification of Waters

Chemical analyses on waters from cold and hot springs, lakes and streams in the Rift Valley have been performed by various people at different times. Data on hot spring and surface water geochemistry in the NW Lake Abaya area is available from 5 different sources including some water sampling done during the present study (Table 7).

The various results on the same waters show certain discrepancies and lack uniformity. These differences seem to depend, to a large degree, on various methods and techniques employed in sampling, handling, preservation and treatment for analysis. A general tendency in the results is sometimes shown. A decrease, for instance, in the constituents of Na, $HCO_3$, and Cl during a period of about 7 years (1973-1980) is apparent, while the silica values of all analyses of Negussie (EIGS, unpublished) always appear greater than those of UNDP (1973). The latter could be due to the method employed, i.e. diluting 10 ml of filtered sample with distilled water to 100 ml to avoid polymerization of silica prior to analysis.

Many of the figures utilized in this paper are those determined by Negussie (unpublished) and occasionally compared with those of UN (1973). Sample designations of UN (1973) will be followed.

Table 8. Chemical Analyses of Surface Waters and Cold Springs

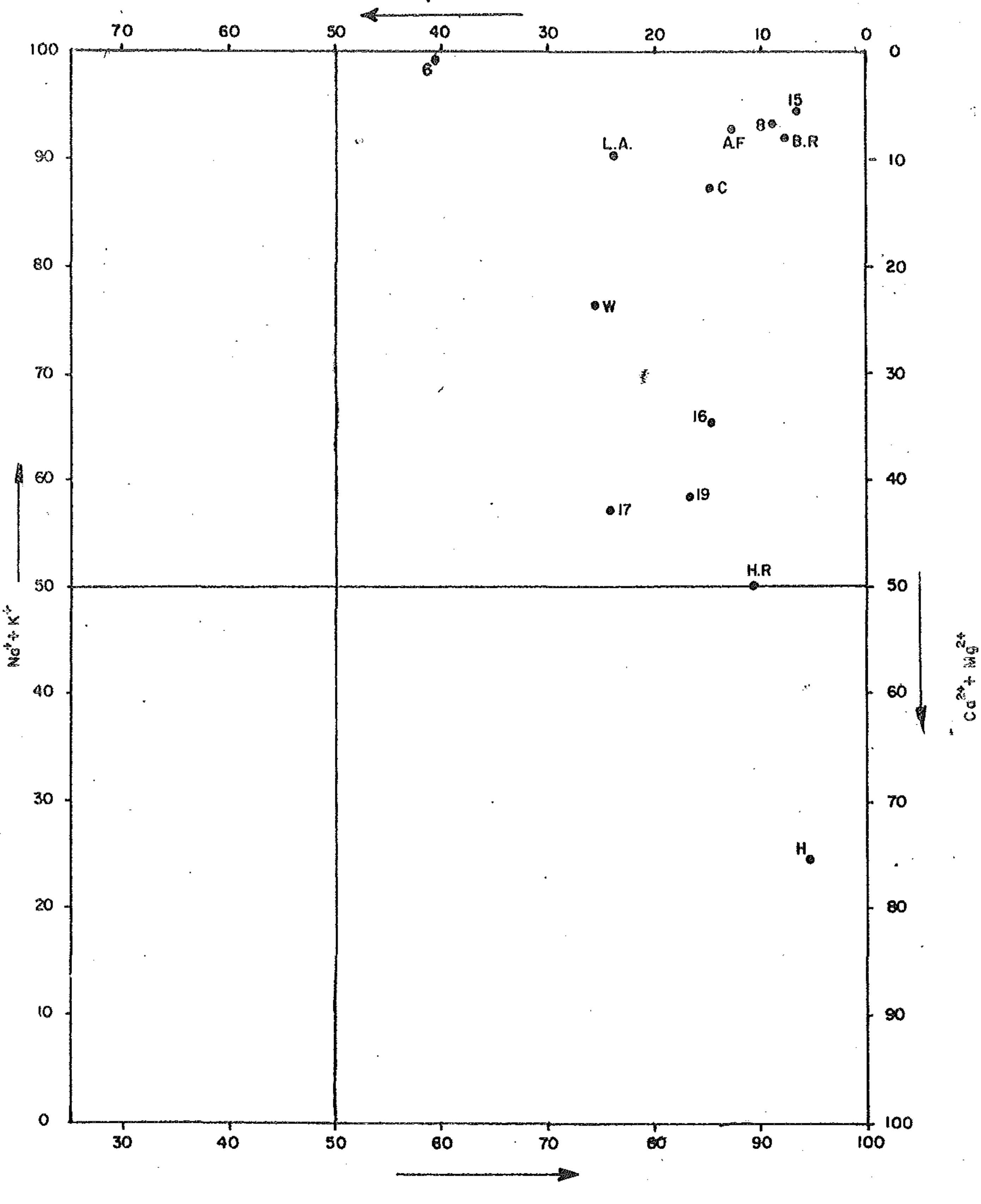
Sources: 1. UNDP (1973); 2. Geroom (unpublished)

| Source | Sample | Concentrations (ppm) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Na | K | Ca | Mg | Cl | $SO_4$ | $HCO_3$ | $CO_3$ | F | $CO_2$ | $SiO_2$ | $HBO_2$ |
| 1 | Lake Abaya | 226 | 20 | 18 | 5 | 41 | 27 | 595 | - | 7 | 4 | 73 | 1.25 |
| 1 | Hamassa River | 92 | 17 | 20 | 7 | 10 | 10 | 293 | 24 | 5 | - | 74 | - |
| 2 | Bilate River (near L. Abaya) | 55 | 9 | 15 | 4 | 13 | ·1 | 195 | 6 | - | - | 42 | .1 |
| 1 | Stream north of Abaya turnoff | 17 | 8 | 8 | 2 | 10 | 10 | 85 | - | 0.5 | 4 | 49 | 0.75 |
| 2 | Dugwell at Abaya Farm | 130 | 18 | 30 | 12 | 2.7 | 17 | 474 | - | 3 | 1 | 9 | 0.1 |
| 2 | Humbo Cold Spring | 18 | 5 | 26 | 5 | 2 | 5 | 171 | - | 0.2 | 18 | 95 | 2 |
| 2 | Chericho borehole | 370 | 26 | 26 | 14 | 82 | 18 | 949 | - | 9.4 | 15 | 62 | 2 |
| 2 | Womba Cold Spring | 15 | 4 | 3 | 1 | 7 | 5 | 45 | 6 | 0.31 | 17 | 77 | 2 |

In the method of Negussie (EIGS, unpublished), two water samples were collected at each site. These were pressure filtered through 0.45 micrometer using a hand pump as a pressure source. To preserve the cations in solution between collection and analyses time, a 250 ml filtered sample was acidified with HCl to pH 1-3. In the field, determinations were conducted on water temperature, pH, $H_2S$, ammonia and the carbonate species using titration methods. The rest of the constituents were determined in the Chemical Laboratory of the EIGS.

Figure 5 represents the chemistry of waters in the NW Lake Abaya area including hot springs, streams and Lake Abaya water. Some hot and cold springs from the surrounding region are included for comparison. The locations of these sample is shown in the map.

Most of the springs fall in a temperature range of 37-67°C. Low contents of Cl (10-81 ppm), low $SO_4$ (10-18 ppm) and low Cl/total carbonate species are the characteristics. All the springs are notable for their high content of dissolved solids, the most abundant dissolved ions being Na and $HCO_3$; silica amounts to 15-20%. The concentrations of Mg and Ca are comparatively low. All the springs evolve $CO_2$ and have high discharges. An exception to this general trend is spring 6 which shows unique characteristics in chemical constituents.




$HCO_3^- + CO_3^{-2}$

Fig.5. LANGELIER – LUDWIG Diagram

| | |
|---|---|
| L.A | Lake Abaya water |
| B.R | Bilate River water |
| H.R | Hamassa River water |
| H | Humbo cold spring |
| W | Womba cold spring |
| A.F | Abaya Farm dry wells |
| C | Chericha bore hole |

The relative abundances of the major chemical constituents in the waters is shown in the diagram of Fig. 6.

The waters have been classified according to the nature of the major dissolved salts which consist of Na, K, Mg, Ca, $HCO_3$, $SO_4$ and Cl. The classification is based on Langelies-Ludwig (L.L) graph (Fig. 5). The points on the graph do not show much scattering. Almost all the samples are grouped within the alkali-bicarbonate quadrant. This dominant position on the graph defines the waters. Figure 7 is a diamond-shaped diagram serving the same purpose as the L.L. diagram.

Detail observation of the diagrams shows that 3 groups occur depending on the chemical composition.

1. Alkali-bicarbonate waters of springs 8 and 15 and those waters from Lake Abaya and Chericho borehole. Prison Farm springs and springs along the Bilate River further north fall within this group.
2. Alkali-alkaline earth-bicarbonate waters of springs 16, 17 and 19.
3. Alkali chloride-bicarbonate sulphate water of spring 6.

Alkali-bicarbonate water is the dominant water type in the Lakes District according to UN (1973). This type of water extends from north Lake Langano to north Abaya represented mostly by all high temperature springs.

In the NW Lake Abaya there seems to be a relation between the waters of Lake Abaya and hot springs 8 and 10. The lake water probably mixes with these springs slightly recharging the underground waters. No clear relation is observed with springs further NE i.e. springs 15, 16 and 19.

The alkali chloride-bicarbonate sulphate water of spring 6 is a unique one in the area. It is not affected by the Lake Abaya water to any degree, though it is found immediately adjacent to the lake shore.

## 4.2. Implications from Chemical Constituents

### 4.2.1. Chloride and Boron

The experimental works of Ellis and Mahon (1964, 1967) on hot water/rock interactions show that Chloride and Boron (and Ammonia) which occur in rocks only to minor extent are easily dissolved at elevated temperatures. These mobile constituents are not incorporated easily in hydrothermal minerals. Mahon (1970) has noted that in areas where high output springs occur, the highest Cl springs are regarded as being supplied directly from a deep source.

The relatively high concentrations of Cl and B in spring 6 indicate that higher temperature conditions prevail in the aquifer supplying it. The relatively lower concentrations of Cl and B in the other springs may be due to relatively low temperatures in the aquifers with which the thermal waters are associated or to a considerable dilution. Spring 16 (Cl = 81 ppm) must be affected less as compared to the other springs.

The Cl/B ratio is of much significance since when more than one group of values occurs more than one aquifer may be indicated (Mahon, 1970; 1980). The Cl/B ratios for NW Lake Abaya springs is given in Table 9.

Table 9. Cl/B ratio in the thermal waters

| Sample Designation | 6 | 8 | 15 | 16 | 17 | 19 |
|---|---|---|---|---|---|---|
| Cl/B | 58 | 21 | 19 | 62 | 3 | 50 |

These ratios suggest that probably two hydrothermal systems exist in this area.

The presence of more than one aquifer at depth is further evidenced by the relationship between chloride concentrations and spring temperatures. If simple mixing is controlling the chloride concentration and spring temperature, a plot of the Cl concentration versus spring temperature should be a straight line (Mariner and Willey, 1976). However, such a plot (Fig. 8 ) shows that

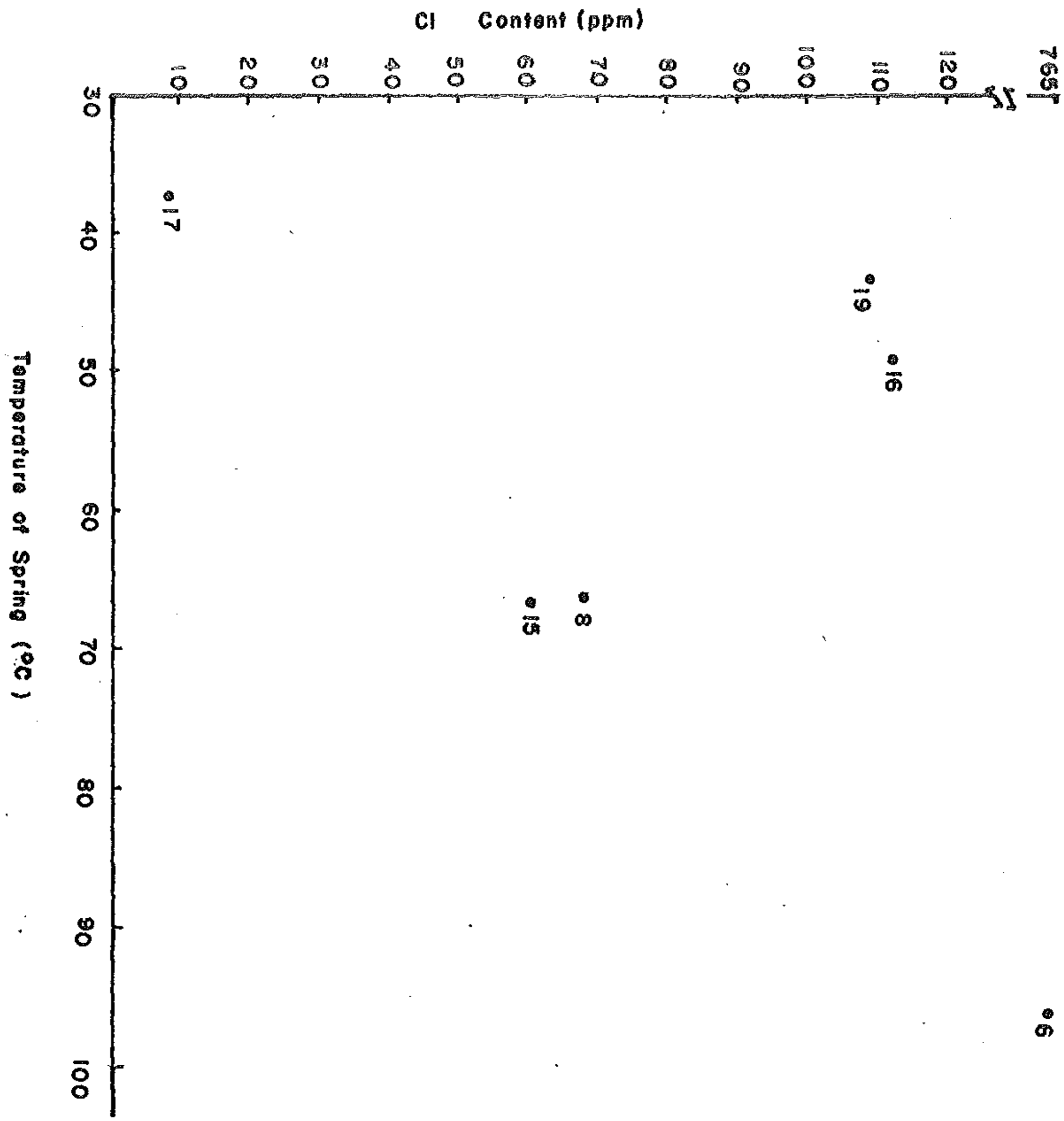



Fig. 8 - GRAPH SHOWING Cl / TEMPERATURE RELATION

a linear relationship does not exist suggesting that the thermal waters come from different aquifers.

The content of Boric Acid is a good indication of high temperature conditions. Boric acid is supplied as the vapor which comes from boiling aquifers and flows towards the surface; above 250°C a considerable quantity is freed along with the vapor (Mahon, 1980). Spring 6 contains the highest concentration of this acid (15.1 ppm). This enrichment not only confirms a high temperature hydrothermal system at depth but also suggests an escape of vapor from the top of the geothermal reservoir supplying spring 6. Ammonia concentration is also relatively higher (1 ppm.) in this spring supporting the above suggestion.

### 4.2.2. Alkali Ratios

Different alkali ratios of the thermal waters result from differences in temperature, mixing, permeability of rocks, etc. The most important alkali ratios are given in Table 10.

Table 10. Alkali Ratios

| Sample No. | Na/K | Na/Li | Cl/F | $Cl/SO_4$ | Na/Ca |
|---|---|---|---|---|---|
| 6 | 9 | 217 | 8.9 | 18.5 | v. high |
| 8 | 17 | 262 | 2 | 10.8 | 44 |
| 15 | 18 | 259 | 1.9 | 10.8 | 51 |

Table 10 Alkali Ratios Cont'd...

| Sample No. | Na/K | Na/Li | Cl/F | $Cl/SO_4$ | Na/Ca |
|---|---|---|---|---|---|
| 16 | 10 | 107 | 22 | 12.2 | 7.7 |
| 17 | 6.8 | - | - | - | 4.1 |
| 19 | 21.7 | 1200 | 1.3 | 11.0 | 61 |

The low Na/K ratio of spring 6 is a confirmation that it has reached the surface quite rapidly with negligible mixing while the rest of the springs have greater values showing a delay probably mixing with a near-surface aquifer. Spring 17 which has a low Na/K ratio is being highly diluted by Hamassa River. The high Na/Ca ratio is a further indication for the direct supply from a deeper aquifer for spring 6. Major contamination, except for springs 6 and 16, is indicated by the Na/Li ratios. Ratios of Cl/F and $Cl/SO_4$ in the studied thermal springs are in good agreement with results from other constituents in showing high temperature for spring 6. The high ratio of spring 16 is an indication of comparatively less contamination with cold surface water.

### 4.2.3. $Cl/(HCO_3 + CO_3)$ ratio

The ratio of equivalents of Cl to equivalents of $HCO_3 + CO_3$ has been found to be very useful in distinguishing waters from different aquifers. For waters from a particular aquifer the equivalent $Cl/(HCO_3 + CO_3)$ ratio will be distinctive, the value decreasing as spring temperature decreases (Mariner and Willey, 1976).

Fournier and Truesdell (1970) found out that for the waters in the Upper Geyser Basin, Yellowstone National Park (USA), there were three different $Cl/(HCO_3 + CO_3)$ ratios corrosponding to aquifers of different temperatures, The highest ratio corresponded to the highest temperature. A similar situation can be thought of the area under investigation. The $Cl/(HCO_3 +$ $CO_3$ ratios Table 11 show that two groups are present indicating the presence of two aquifers. Spring 6 with the highest ratio corrosponds to the highest temperature. Spring 16 probably originates from the same aquifer as spring 6 but has been diluted by near-surface water.

Table 11. $Cl/(HCO_3 + CO_3)$ ratio in the thermal waters

| Sample Designation | [illegible] | 6 | 8 | 15 | 16 | 17 | 19 |
|---|---|---|---|---|---|---|---|
| $Cl/(HCO_3+CO_3)$ | UN (1973) | 0.8 | 0.061 | 0.061 | 0.165 | - | 0.121 |
| | Negussie (unpublished) | 0.56 | 0.08 | 0.07 | 0.22 | 0.04 | 0.20 |

#### 4.2.4. Other Ratios

To emphasize on the phenomena of mixing, two more ratios are quoted, B/Na and Na/Ca ratios. A constant B/Na ratio is considered to show a common source of hot water (Dominico & Samilgil, 1970). This ratio (Fig. 9 ) in the studied springs does not show any regular pattern. There seems to be a considerable dilution by colder B-free shallow water of the springs except that of spring 6.

The mixing proportions between the deep hot water and the cold waters are also shown by the inverse proportionality linking Na to Ca (Fig. 10).

### 4.3. Chemical Geothermometers

The various chemical geothermometers have been applied in many places for geothermal reservoir temperature evaluation. Of the various proposed ones the silica concentrations and alkali ratios of Na/K and Na-K-Ca in the thermal fluid have been demonstrated to have widspread application. The concentrations of $CO_2$, methane and ammonia in steam discharged from fumaroles have also been used.

#### 4.3.1. Silica

The dissolved silica content of thermal waters have been utilized by many scientists in many geothermal areas to estimate subsurface temperatures in aquifers feeding hot springs, Silica concentration in solution is independent

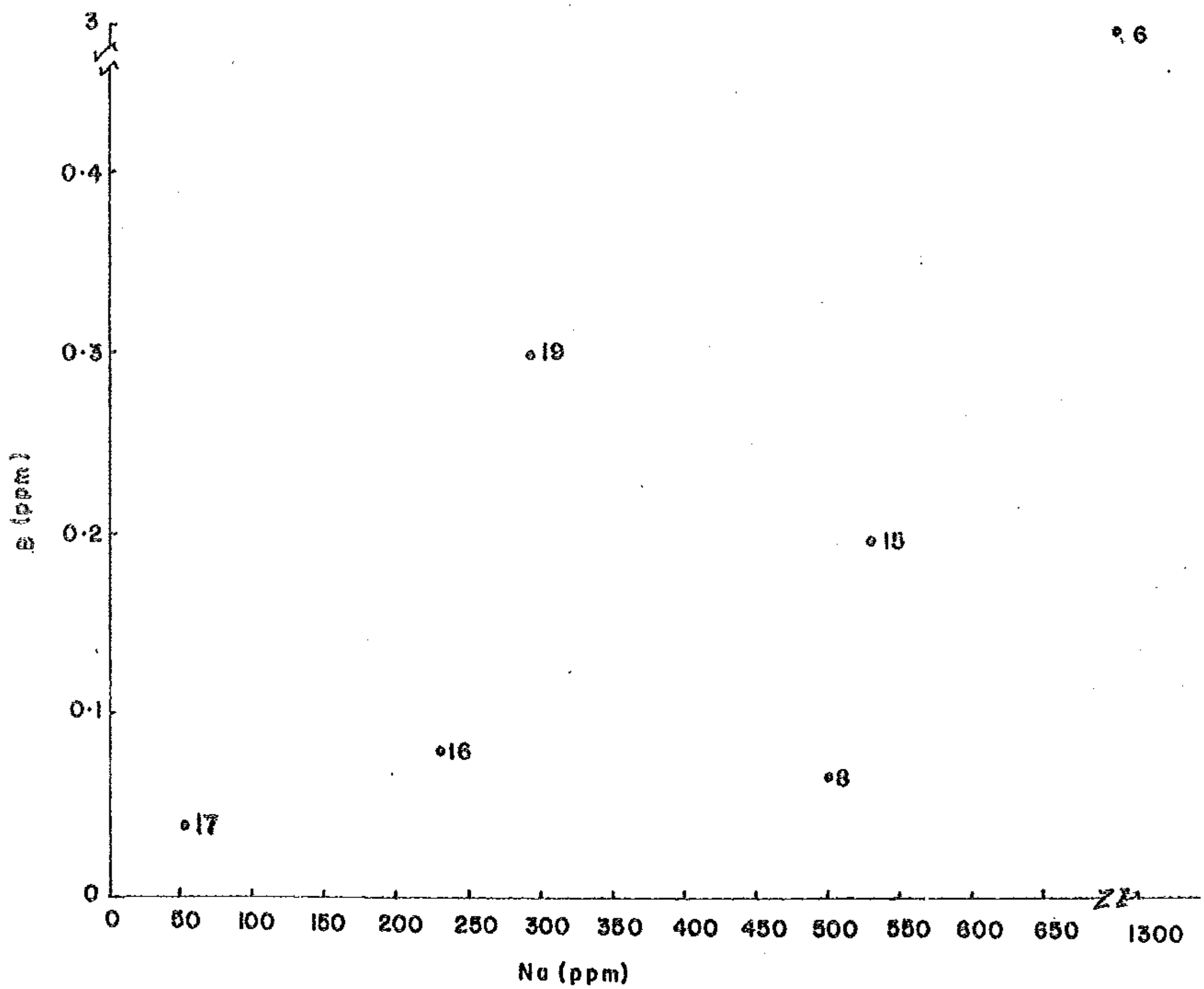



Fig. 9 GRAPH SHOWING B/Na RELATION IN THE THERMAL WATERS

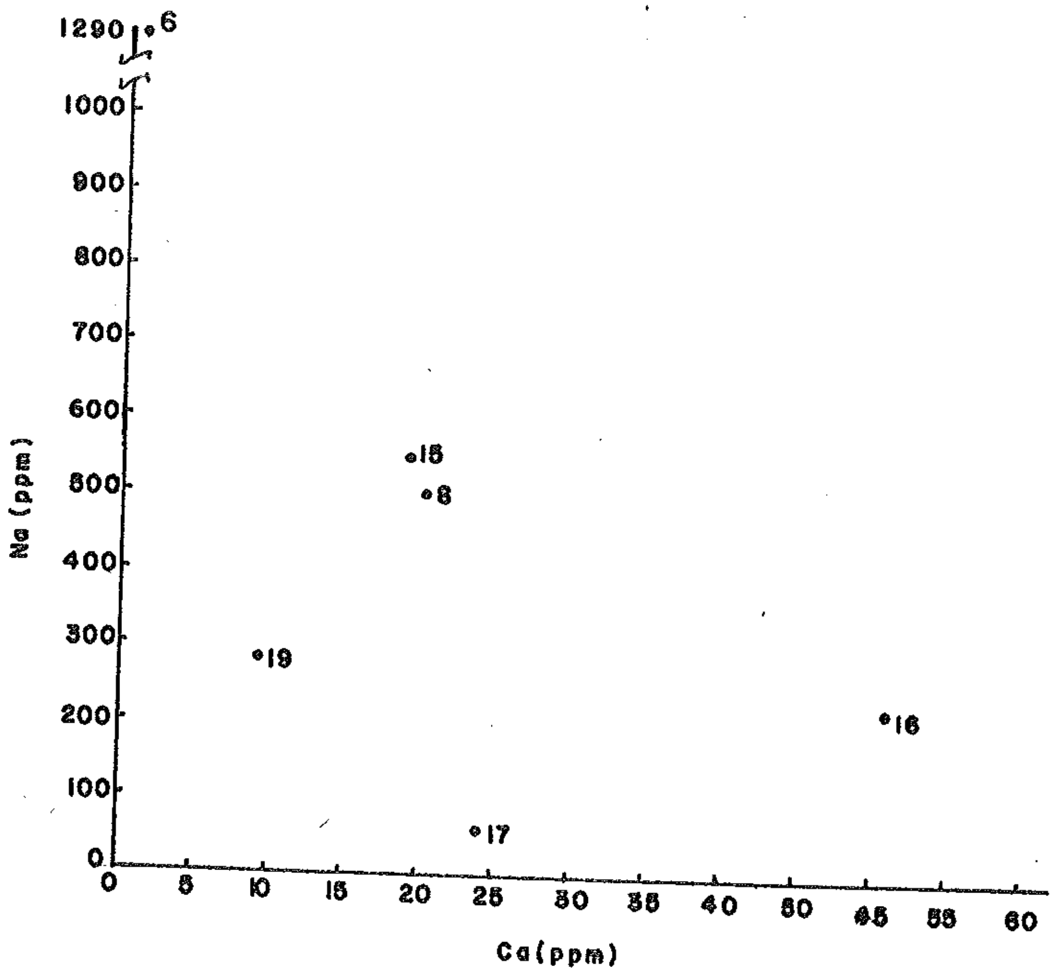



Fig.10-GRAPH SHOWING Na/Ca RELATION IN THE THERML WATERS

of other ions and pH but strongly depends on temperature. The water with the highest silica content in any thermal area bears the closest resemblance to the deep water of that area and also indicates the zone of major upflow of deep water (Ellis and Mahon, 1967).

In the studied area, the various hot springs have different silica values from the various analysis results (see Table 7). The differences in the results have serious effects on the estimated temperatures. All analyses data, however, show that spring 6 has the highest silica content in the whole area. Here a considerable amount of siliceous sinter deposition is also present. According to White et al., (1971), waters that deposit sinter nearly always have $SiO_2$ contents of at least 240 ppm equal to a temperature of $180^{o}C$. The various analyses data on silica contents in Lake Abaya area can be evaluated from this general observation.

Temperatures estimated from the concentration of silica based on curves from the work of Fournier and Rowe (1966) relating silica content to the temperature at which the water was last in equilibrium with quartz, are listed in Table 12.

Table 12. Estimated Silica Temperatures

| Sample Designation | Silica content (ppm) | | Silica Temperature (°C) | |
|---|---|---|---|---|
| | UN (1973) | Negussie (unpublished) | UN | Negussie |
| 6 | 204 | 428 | 177 | 216 |
| 8 | 146 | 167 | 156 | 159 |
| 15 | 141 | 180 | 154 | 156 |
| 16 | 116 | 128 | 142 | 146 |
| 17 | 122 | 133 | 145 | 147 |
| 19 | 126 | 133 | 147 | 147 |

Two groups of temperature values are apparent from these estimations. A higher temperature reservoir of deep origin represented by spring 6 and a lower temperature reservoir of relatively shallower origin giving rise to the rest of the hot springs. The temperature so estimated for each spring is the temperature of last equilibrium and higher temperatures can be present.

4.3.2. Alkali Ratios

4.3.2.1. Na/K

It has been shown that base exchange of alkalis between solution and solid phases is temperature dependent. Thus indications of subsurface temperature are given by alkali ratios in natural geothermal waters. Curves showing suggested atomic Na/K ratios versus temperature are given in several papers. Care must be taken in applying this ratio in that it may be greatly affected by dilution with shallow low-temperature water. It has been also observed that for geothermal systems in which temperatures do not exceed 180°C at depths of less than 300 m, Na/K assessed temperatures are not reliable, especially where Na bi-carbonate/carbonate solutions are present (Mahon, 1980).

Table 13 gives the estimated Na/K temperatures for the studied hot springs around NW Lake Abaya area.

Table 13. Estimated Na/K Temperatures

| Sample Designation | Na/K Temperature (°C) UN (1973) | Negussie (unpublished) |
|---|---|---|
| 6 | 265 | 237 |
| 8 | 187 | 167 |
| 15 | 180 | 160 |
| 16 | 220 | 208 |
| 17 | 270* | 234 |
| 19 | 120* | 220 |

* not given by UN

As mentioned above, the evidence of considerable dilution in most of the springs makes the estimated temperature values less reliable as representing the reservoir temperatures.

4.3.2.2. Na-K-Ca

Mixing phenomena which sharply decreases the concentrations of dissolved silica, affects the cation ratios of Na-K-Ca less and as a result the cation geothermometers should produce an estimate nearer the true reservoir temperature (Mariner and Willey, 1976). It has also been observed that the amounts of aqueous Na and K are influenced by the Ca concentration and that Ca should sometimes be considered.

Fournier and Truesdell (1973) considering reactions involving only aqueous Na, K and Ca have constructed a straight line curve which may serve as a useful referrence for geothermometry of many waters. The resulting graph is used to estimate temperatures of last rock-water equilibrium.

Table 14 shows the temperatures found for the springs of NW Lake Abaya area using Na, K, and Ca values from UN (1973) data. Estimated temperatures by Negussie (unpublished) are also shown.

Table 14. Estimated Temperatures Using Na-K-Ca

| Sample Designation | Estimated Temperatures (°C) | | | |
|---|---|---|---|---|
| | Using UN (1973) Values | | Negussie (unpublished) | |
| | $\beta = 1/3$ | $\beta = 4/2$ | $\beta = 1/3$ | $\beta = 4/3$ |
| 6 | 300 | - | 947 | 1407 |
| 8 | 200 | 210 | 227 | 380 |
| 15 | 200 | - | 232 | 446 |
| 16 | 215 | 165 | 231 | 321 |
| 17 | 220 | 100 | 187 | 86 |
| 19 | 190 | 180 | 218 | 128 |

Deep temperatures using gas geothermometers have been calculated by Glover (1976). Gas equilibration temperature for spring 6 has given a value of 169°C.

Craig (1977) calculated and assessed deep temperatures using the O-18 differences between oxygen in the sulphate ion and in the water itself. The calculated temperature for the Lake

Abaya area is 325$^{o}$C using the lake water.

A comparison of the estimated temperatures using various methods is presented in Table 15.

Table Comparison of Estimated Temperatures by Various Methods

| Sample Designation | $SiO_2$ | | Na/K | | Na-K-Ca | | $CH_4$ | O-18 |
|---|---|---|---|---|---|---|---|---|
| | UN (1973) | Negussie (unpublished) | UN | Negussie | UN | Negussie | Glover (1976) | Craig (1977) |
| 6 | 177 | 216 | 265 | 237 | 300 | 947 | 169 | 325 |
| 8 | 156 | 159 | 187 | 167 | 200 | 227 | - | - |
| 15 | 154 | 156 | 180 | 160 | 200 | 232 | - | - |
| 16 | 142 | 146 | 220 | 208 | 215 | 231 | - | - |
| 17 | 145 | 147 | 270 | 234 | 220 | 187 | - | - |
| 19 | 147 | 147 | 120 | 220 | 190 | 218 | - | - |

From Table 15 it can be observed that temperatures estimated employing Na-K-Ca and O-18 methods are much higher than those obtained from other methods and are regarded to be tentative. Some figures as the Na-K-Ca values (of Negussie for spring 6) are totally unacceptable and could be due to errors in calculation procedure. In many of the cases the silica and Na/K derived temperatures are in reasonable agreement.

Though more definite conclusions are difficult to take (due to large discrepancies in the obtained figures) some generalizations can be drawn from the data. All methods show that spring 6 is associated with reservoir temperatures greater than at least 169°C. A temperature of 200°C seems to be a reasonable value from the comparison of all the estimations for the thermal reservoir feeding this spring. Higher temperatures are possible. It is of interest to note that the deep temperature found for this spring is the highest in the Lakes District indicated by surface chemistry (Mahon, 1980). The other springs are fed by a different and shallower reservoir of minimum temperature of 142°C. Higher temperatures are possible because the evidenced dilution affects the various constituents used for temperature determinations.

4.4. Isotope Geochemistry

According to Craig (1977), the only significant heavy oxygen shifts found in hot waters in the Lakes District were on the north shores of Lake Abaya and Lake Langano. Spring 6 showed an oxygen-isotope shift of about 2.3 per mil (see Fig. 4 and Table 5). This result is interpreted to signify the presence of high temperature hydrothermal reservoir in this locality if one assumes that the O-18 contents of the aquifer rocks for the deep hot waters are different from those present in the waters themeselves. The isotopic work leads to the conlcusion, as forwarded by Craig (1977), that spring 6 is the only evidence for high temperature sub-surface water reaction in the NW Lake Abaya area and that the water has circulated to some depth.

## 4.5. Gas Chemistry

Gas composition depends to a large extent, on the temperature, and due to the high activation energy of $H_2$ and $CH_4$ molecules, remains unvaried under 300-400°C (Aquater, 1979). Steam boiling off the top of deep aquifers may be discharged from fumaroles and areas of steaming ground.

The composition of gas in steam discharged from the Abaya Fumarole which is associated with spring 6 is given by Glover (1976) and shown in Table .

Table 16 . Gas analyses (After Glover, 1976)

Gas concentrations in the steam (in mM/100M)

| | Abaya Fumarole | Spring 6 |
|---|---|---|
| Total Gas | 6494 | - |
| $CO_2$ | 6430 | - |
| $H_2S$ | 4.29 | - |
| $NH_3$ | 1.3 | n.a. (not analysed) |
| $NH_3$ (in mg/l) | 1.2 | n.a. |

Gas composition expressed as percentage of gas

excluding $H_2O$

| | | |
|---|---|---|
| $CO_2$ | 99.01 | 99.56 |
| $H_2S$ | 0.066 | 0.006 |
| $NH_3$ | 0.02 | n.a. |
| $H_2$ | 0.003 | n.a. |
| $O_2$ | 0.178 | 0.097 |
| $N_2$ | 0.432 | 0.33 |
| $CH_4$ | 0.29 | 0.0012 |
| % air in Total gas | 0.55 | - |
| % air in residual gases | 60.83 | 96.9 |
| Excess $N_2$ (as % of total gas) | - | - |
| Excess $O_2$ (as % of total gas) | 0.062 | 0.013 |

Gas Ratios

| | | |
|---|---|---|
| $CO_2/H_2S$ | 1500 | 1600 |
| $CO_2/H_2$ | 30000 | |
| $CO_2/NH_3$ | 5060 | - |
| $CO_2/CH_4$ | 350 | 83000 |
| $H_2S/NH_3$ | 3.38 | - |
| $H_2/CH_4$ | 0.012 | - |

The major gas is $CO_2$ which contributes 99% while the rest make-up the residual. The origin of this gas (according to Craig's (1977) C-13 measurements) come from equal amounts of plant-derived $CO_2$ in solids and carbonate carbon, although this origin is doubted by Mahon (1980).

The importance of $CO_2$ content can be visualized by comparison with amounts found in explored geothermal fields. Browne and Ellis (1970) (according to Mariner and Willey, 1976)reported that the noncondensable fraction of 5 steam wells in the Ohaki-Broadlands field contained 92-95% $CO_2$. Noncondensable gases from Steam Boat, Springs, Nevada, (USA) contain an even larger amount (98% $CO_2$).

From the variations in gas concentrations, and ratios between gases, Glover (1976) concluded that the Abaya fumarole was the most vigorous sampled in the Lakes District and the steam discharged was most likely to represent the deep steam composition.

Gas ratio results indicate very high $CO_2/H_2S$ ratio (1500) for Abaya Fumarole. This high ratio has been explained to result from high partial pressures of $CO_2$ at deep levels in the system with due allowance to the waters and steam having undergone considerable interaction with rocks and/or cold meteoric water before reaching the points of discharge; $CO_2$ partial pressures for the deep water in Abaya area has been calculated to be around 80 bars(Mahon, 1980). This high underground partial pressure of $CO_2$ suggests that considerable calcite deposition occurs resulting in considerable sealing of underground reservoirs. This is especially true when boiling takes place and probably explains the apparent absence of major discharges of boiling water at the surface.

Ranges of possible concentrations of gases in the deep aquifer have been assessed for Abaya area and $CO_2$ concentrations in the range between 2.5 and 3% by weight are thought to exist at depth (Mahon, 1980).

The escapes of gases are suitable for determining permeability since accumulation of gases is favoured in a high permeability zone from which the gases escape towards the surface as a result of hydraulic uplift. In the case of Abaya Fumarole the high permeability zone coincides with the fracture produced by the Chokare fault.

From the above discussion it can be concluded that the chemistry of the thermal waters in the NW Lake Abaya area is consistent in showing the presence of two aquifers at depth. Spring 6 represents a relatively deeper hydrothermal system at comparatively high temperature whereas the rest thermal springs show evidences of considerable dilution by a shallow cold groundwater and surface waters. Variations in chemical compositions of the springs, excepting spring 6, is probably the result of reaction of the hot solutions with rocks at relatively shallow levels and various proportions of mixing with near-surface groundwater.

The NW Lake Abaya hot spring system can be thought of as a major liquid flow from the deep aquifer, due to the high concentration of non-volatile substances. On the whole, a clear and important leakage anomaly that can be ascribed to steam is not observed in the hot springs. The highest values of B and $NH_4$ (3.1 ppm and 1.00 pm respectively) are recorded in spring 6. These concentrations appear to be an original feature of the deep water and not a result of steam leakage. This further suggests that the geothermal aquifer is primarily a liquid flow, the composition of which can be approximated by the chemistry of spring 6.

## 5. Geoelectrical Survey Results

Electrical methods have been successfully employed in a number of places for exploration for geothermal energy resources because of the direct relationship between fluid and rock temperatures on one hand, electrical conductivity on the other (Keller and Rapolla, 1974). In general the resistivity of a rock formation decreases with increase in temperature. The bulk resistivity of rocks in significantly affected by the presence of clay minerals which can be products of hydrothermal alteration especially at greater depths.

Various methods of electrical resistivity measurement are employed for geothermal purposes, which include horizontal profiling, vertical electrical sounding (VES) and dipole-dipole array (Dobrin, 1976 ).

In the method of horizontal profiling the array of electrodes is moved laterally along a profile taking the electrode spacing fixed and the apparent resistivity is referred to the midpoints of the electrical line. The bodies with resistivity change which are located at the depth of maximum effective penetration of the electric current, show up as an anomaly on the resulting map.

In VES, the center of the electric line remains fixed but the separation of electrodes is progressively increased. In a dipole-dipole survey, the current electrodes are fixed but the potential electrodes are moved laterally along a profile.

The resistivity survey in the NW Lake Abaya area was carried out by EIGS. The available data has been interpreted by Jihad (1980). Resistivity surveys using horizontal profiling, VES and dipole-dipole array methods were employed.

According to Jihad (1980) the horizontal mapping covered 10 lines of total 52 km length and covered an area of about 40 $km^2$. A fixed current spread of AB/2 = 1000 m was employed. Only a single VES was done to effective depth of 1500 metres. The dipole-dipole array survey used dipole length (a) of 500 metres with N values from 2 to 7 thus making the maximum distance between the centres of electrodes equal to (Na) 3.5 km. Only 5 lines were performed, none of which was complete.

5.1. Horizontal Profiling

The result of the Schlumberger apparent resistivity map is shown in Figure 11. A closer look at this map shows that there are two areas of low resistivity defined by apparent resistivity values of $< 5$ ohm-meter. One of this areas is found along the Chokare fault. This zone has an extension of about 6 km in NNE direction. It is about 300 m wide in its northern part but much wider in the southern portion with a width of more than 2 km. The southern limit extends into Lake Abaya.

A second area of low resistivity ( $< 5$ ohm-meter) is located just east of Abela village. The size of this zone is not well delineated due to insufficient data. It extends further northwards as shown by the open contours.

5.2. Dipole-Dipole Results

This survey depicts more the electrical structure in two-dimensions, lateral and vertical extension when the data are plotted on pseudo-sections as performed by Jihad (1980). These sections are shown in Figs. 12a-12e at 1/15,000 scale.

The pseudo-sections show that low resistivity area extends to depths between 500 to 1000 m approximately. Although the data are incomplete an attempt is done to outline the size and shape of the low resistivity zone. This is shown in Fig. 13 which shows the low resistivity zone (5 ohm-m). The result from horizontal profiling is also shown for comparison. It is observed that an east-west extension of about 2.5 km is apparent. The length in the north-south direction is not known since it extends in both north and south directions. A size not less than 6 km is indicated.

5.3. Vertical Electrical Sounding (VES)

From data obtained on the single VES conducted north of spring 16, near the base of Chokare fault scarp, Jihad (1980) has constructed a curve of apparent resistivity versus spacing AB/2. This curve is shown in Fig. 14 Eventhough the curve is a complex one, an attempt has been done to present a general model from this curve using theoretical master curves.

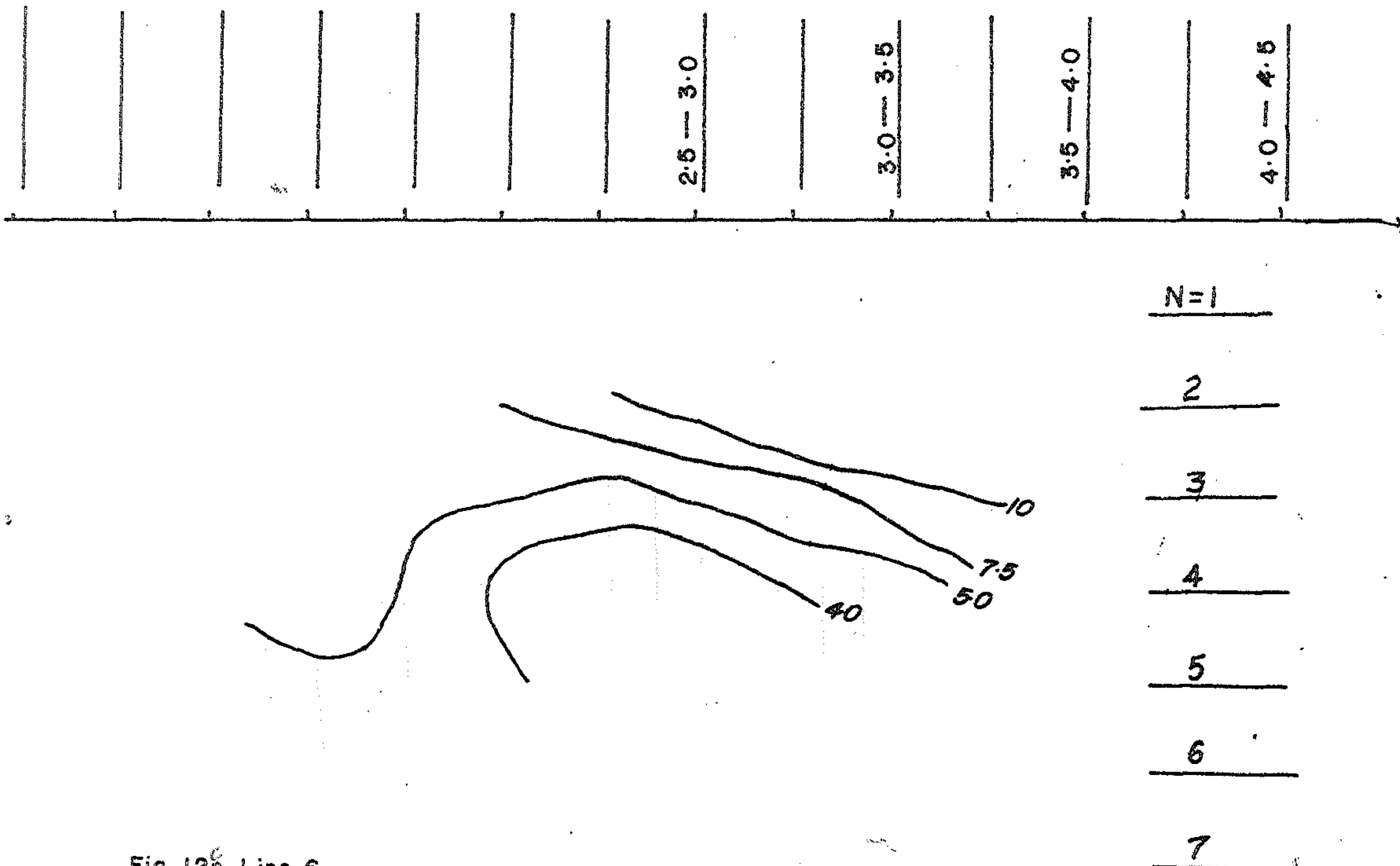
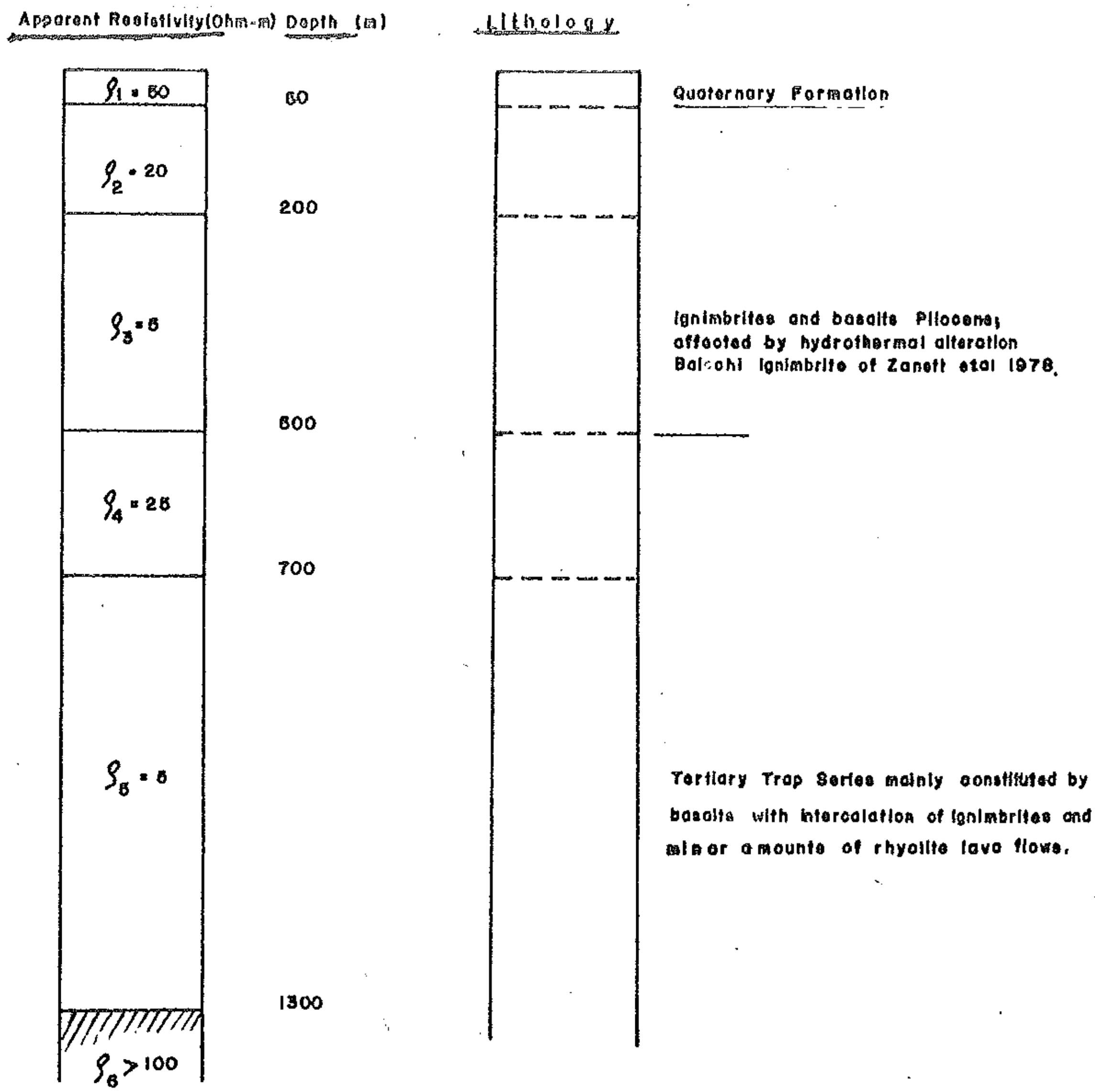



Fig. 12c, Line-6

Fig.15-Electrostratigraphy from VES Correlated with Geology



young basaltic flows and the deposits of pumice and ash which show no hydrothermal alteration. The second layer corrosponds nicely to the Chokare ignimbrites, eventhough, the thickness of this formation is unknown.

Underlying the Chokare ignimbrites a formation consisting of ignimbrites (and basalts) of Pliocene age is expected to be present. This formation together with the bottom portion of the Chokare ignimbrites can represent electric layer 3.

Underlying the ignimbrites and basalts consituting layer 3, we expect to find Tertiary trap series mainly constituted by basalts with intercalations of ignimbrite and minor rhyolitic lavas. The presence of basaltic rocks at a shallower depth is evidenced from xenoliths in Chokare ignimbrites. These rocks, the exact succession of which is unknown, are considered to constitute the last three layers. The variations in resistivity within these rocks results most probably from contained fluids (at probable higher temperatures) as well as the effect of altered products.

The relatively higher resistivity of electric layer 4 might be explained by two possible alternatives. The first possibility is that the uppermost part of the Tertiary trap series is constituted of deeply weathered and altered zone which represents a possible short time gap before the onset of the Plio-Quaternary volcanic activity. Another possibility is that the higher resistivity results from a zone of alteration within the same rock formation constituting the deep reservoir. This possibility has the drawback that such a layer would have given a lower resistivity value than that obtained. However, the absence of hot fluids can comparatively raise the resistivity value here.

The resistive substratum found at depths of 1300 m is probably constituted by the same Tertiary trap series formations. The absence of water and hydrothermally altered products together with possibly low permeability must be governing the very high resistivity measured.

## 6. Preliminary Geothermal Model

The basic objective in any geothermal exploration work is the definition of a geothermal model which expresses the fundamental conditions of a geothermal field. These conditions consist of the heat source, the reservoir and the caprock.

### 6.1. Heat Source

It is accepted, from both geological and geophysical evidence, that attenuated crust underlies the Ethiopian Rift, where in the growing gaps volcanic activity strongly dominate.

Searle and Gouin (1971), from seismic evidence that the Sn phase is attenuated over parts of the East African system to the south-west, conclude that there is a very broad region of low velocity upper mantle centred on the Afar triple junction and wedging out away from the rifts. The upper mantle in this region is presumed to be at higher temperatures, implying a higher than average heat flow. Ruegg (1974), from seismic results, has found that the upper mantle in the Djibouti region is characterized by anomalously low velocities similar to those found in the axial zones of the world rift system. Such anomalous low velocities in the newly created lithosphere have been explained by the presence of partially melted materials.

Girdler (1977) gives a possible interpretation of the overall gravity anomaly over East Africa. This interpretation (Fig.16) shows thinning of the lithosphere

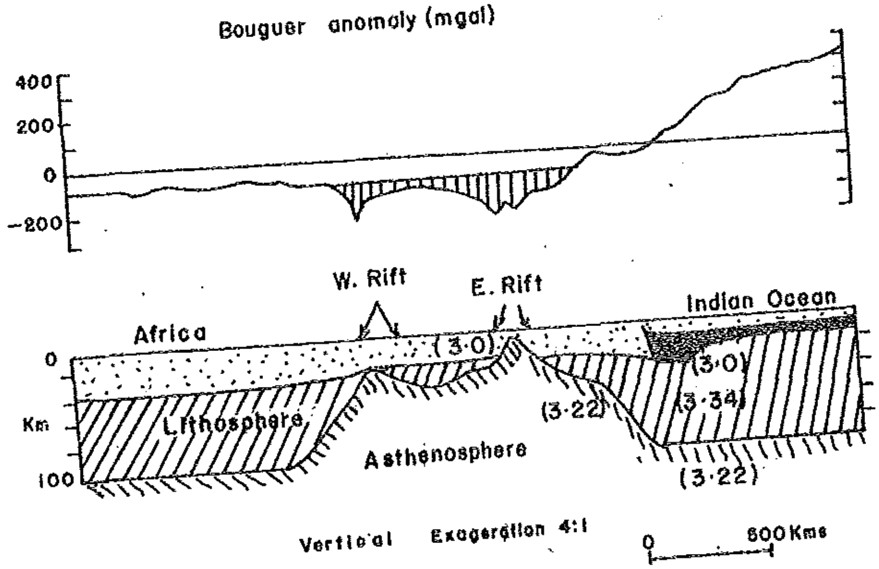



Fig.16 A possible interpretation of the overall gravity anomaly over East Africa showing thinning of the lithosphere beneath the whole region with extreme thinning beneath the rift floor in Kenya.

(After Girdler, 1977)

beneath the Rift floor in Kenya.

Further detailed investigation of geophysical interpretation in the south Kenya Rift (Baker et al., 1977) shows the presence of a zone of hot, partially molten mantle under the Rift with emplacement of basic intrusive rocks in the crust which are present in intra-crustal chambers at not a great depth.

From plate tectonics analysis, Le Pichon and Franch-teau (1978) have indicated that a relative motion of about 30 km across the Ethiopian Rift has occurred in a NNW direction. This conclusion is substantiated by geodetic measurements conducted by Mohr et al., (1978) who showed that small amounts of movements of the order of 5 mm/yr is occurring at present within the most active part of the Rift. Lateral spreading, eventhough very small, is thus in progress. In conclusion and as already discussed, all geological, magmatological and geophysical data indicate the Ethiopian Rift Valley as the site of important continental crust attenuation and the Afar Depression as an embryonic oceanic spreading region.

As observed in other areas, oceanic spreading axes and active continental rift areas are associated with higher heat flow than normal as a result of upwelling mantle material. From these considerations the Rift in Ethiopia is expected to show higher heat flow than the surrounding plateau areas. The abundance of young silicic rocks of peralkali rhyolitic magma observed within the Rift, both as central volcanoes and as fissure products, are mainly distributed within the active central part. This recent volcanism assures immense thermal energy resources. Eventhough a lot of argument still prevails as to the mechanism of origin of these rocks, fractional crystallization of a transitional basaltic magma seems to be the likely origin of at least most of these rocks.

It is presumed from these considerations that magma chambers which feed these lavas exist within the crust probably at a relatively shallow depth (less than 10 km). These magma chambers together with the anomalously high heat flow in the Rift is believed to be the source of heat for the hot springs which are widely distributed all along the Ethiopian Rift. It is important to note that thermal springs in the Rift are in most of the cases associated with acidic volcanism clearly indicating that the heat origin is naturally related to magmas which are responsible for the generation of the recent silicic products.

Anyway, the presence of magmatic heat sources located at relatively shallow depth in many areas of the Rift system of Ethiopia is now widely accepted. What is important to understand is the relative importance of the different heat sources and their most probable location and distribution within those areas already selected for geothermal research.

In the case of the area north of Lake Abaya, the heat source can have two possible meanings.

The first possibility is that the Quaternary tectonic activity in this area was such that the subcrustal magma rose very fast through deep and narrow fissures without stopping at shallow depth to undergo crystal fractionation. The only, but very localized, exception to this mechanism should be represented by the Holocene Salodere-Hoko peralkali rhyolitic lava domes. In this case the only thermal supply of the hot springs along the Chokare fault would be represented by a rather small silicic magma body at present under cooling beneaths the Salodere-Hoko domes. A possible minor contribution of heat could be provided by the central silicic volcano Duguna located about 35 km to the NE which was in activity until at least 0.4 m.y. ago (Bigassi et al., 1979) and at present in a fumarolic stage. The heat source does not need to be directly beneath the thermal manifestations. The groundwater from the recharge areas as it travels through the thermally anomalous zone is heated up and later comes out at the discharge area. In this assumption the heat source eventhough not negligible, should be regarded more as of local than as of regional importance.

The second possibility is that the Quaternary tectonic activity in this area was such that great quantity of subcrustal magma were trapped at relatively shallow depth in many segments of the area north of Lake Abaya. The basaltic magma therefore had large possibilities of producing a much greater volume of differentiated products and not only those now represented by the Salodere-Hoko silicic domes. In this case the heat storage at shallow depth should not be represented only by the presently cooling silicic magma beneath the Salodere-Hoko domes, but by a much greater volume of magma widely distributed and not necessarily extremely silicic. In this assumption, the magmatic heat source in the NW Lake Abaya area should have, definitely, a great regional importance.

At present it is not possible, due to the lack of sufficient data, to make a sharp choice between these two possibilities. However, there are some indications which point towards the second possibility.

a) As already mentioned, there are other important thermal manifestations located to the east and NE of the Chokare fault (Prison Farm Springs, Bolocho Springs, springs widely distributed along Bilate River.....) which are unlikely to be fed by a unique and relatively small heat source as the one localized beneath the Salodere-Hoko domes.

b) The occurrence of faulted-tilted blocks within the area suggests the possibility of important tectonic traps at depth where magma may have stopped to undergo differentiation.

c) As already discussed, there are some, eventhough insufficient, petrographic evidences which may suggest the existence in the whole area north of Lake Abaya of rather important volumes of intermediate rocks which might confirm the existence of a magma chamber of regional extent.

The second possible meaning of the heat source in the area north of Lake Abaya is, therefore, favored in the present study. This could be definitely proved only if a detailed future work will be done at least according to the suggestions that will be specified later.

6.2.2. The Reservoir

The large number of thermal areas in the Rift and the high temperatures of the thermal waters issued, are both indications of a considerable flow of groundwater through the lower parts of the Rift volcanic series. In the NW Lake Abaya area, the existence of one or more aquifers at depth is indicated by the escapes of thermal fluids occurring along the Chokare fault and in the vicinity of Salodere and Hoko rhyolitic domes. Similar indications occur at localized places north of Lake Abaya along Bilate River, as well as along Hamassa River to the south.

The near-surface rocks include rhyolitic domes, basaltic flows with interbeded scoriaceous layers, pumice and ash deposits and ignimbrites. It appears that these rocks, some of which have been hydrothermally altered, do not possess high permeability and as a result do not constitute a high temperature geothermal reservoir. Thus any significant geothermal resource in the area should be in the underlying rocks. The most appropriate formations would be the Tertiary ignimbrites and basalts of considerable thicknesses for deep-seated aquifers. Xenoliths of basic fragments in the Chokare ignimbrites indicate the presence of basaltic rocks at a relatively shallow depth underlying the near-surface rocks.

The pattern and distribution of recent fracturing suggests that secondary permeability due to tectonism must have increased the bulk permeability of the underlying rocks. It is at the same time believed (Isita y Septien, 1970) that even low permeability formations, provided they have large thicknesses, can be suited for geothermal exploitation.

In many explored geothermal fields, the rocks making the permeable deep aquifers are of various lithologic types ranging from primarily impervious compact rocks through medium permeable to highly permeable formations. At Larderello (Italy), Mesozoic evaporitic formation constitutes the aquifer (Marinelli, 1969). In the Geysers (California, USA) the aquifer is made up of graywacke, serpentinite and basalt, whereas in Iceland the aquifer is a fractured basalt (Ellis, 1967).

With the above considerations, the presence of potential aquifers in the NW Lake Abaya area cannot be doubted. However, without deep geologic sections, it remains to be a mere speculation to discuss on definite formations suitable for reservoir storage at depth.

A number of evidences suggest the presence of more than one aquifer in the studied area. Firstly, as mentioned above, all the hot springs in NW Lake Abaya area occur along the Chokare fault. The springs along the Bilate River seem to be controlled by an older lineament of N15$^{o}$E direction (Hochstein, 1980) later covered by younger volcanic products. This suggests that major fractures are acting as conduits for fluids from some deeper zone. Secondly, the springs yield two groups of geochemically derived temperatures and have non-identical chloride-boron ratios implying that the springs are not tapping a single aquifer. The isotopic data which shows an important oxygen shift for spring 6 (not for other springs) is another evidence suggesting that at least two aquifers exist at depth. Finally, the preliminary geoelectric result leads to a model with two aquifers. The shallow low resistivity zone probably represents a near-surface groundwater system. This system is probably heated by fluids from the deeper hot reservoir. This aquifer can be utilized for water supply and possible irrigation purposes, but is of no importance from the geothermal aspect.

A conclusive interpretation of the geoelectric results cannot be made until more detailed work is performed. It can, however, be considered, that the low-resistivity zones outlined in the NW Lake Abaya area result from the effects of both hot water contained in the rocks and hydrothermally altered rocks at depth. Eventhough the clay minerals which are products of hydrothermal alteration of various rock minerals are sometimes in large contents as observed in cores from some geothermal regions, the effect of hydrated thermal alteration products on the electrical resistivities of rocks must not be overemphasized. It is thought that hot and mineralized fluids have a much more dominant effect on the observed low resistivities in the NW Lake Abaya area.

## 6.3. The Problem of the Cover

Concerning the cover for the geothermal reservoir at depth, rocks of low permeability of primary origin like the fluviolacustrine sediments (of limited aerial extent) and possibly the crystal-rich compact ignimbrite unit of the Chokare ignimbrite formation, are thought to act as cover formations to a minor degree. Interbeds of siltstones and claystones are reported to be present in volcano-sedimentary formation which extends outside the area of study (Berhane et al., 1978). The presence of such interbeds within the pumice and ash deposits eventhough not indicated, is not excluded at places especially north-east of Chokare. The presence of clay and silt layers is also possible at some place at depth beneath the Chokare ignimbrite formation. Such units would constitute part of a potential cover at places if the layers are thick and continuous. The absence of thermal manifestations of larger aerial extent is an indication of the presence of some sort of cover at depth which impedes the escape of thermal fluids and heat, eventhough, such a cover formation cannot be determined from surface geology.

More important for the problem of the cover, is the process of hydrothermal alteration within the rocks which can result in self-sealing mechanism at depth. This process produces insulating cap of low permeability clays. The high $CO_2$ content causes precipitation of carbonates in the overlying rocks. Higher temperatures have also resulted, at places, in the precipitation of silica. Such phenomena of the prolonged effects of thermal activity resulting in secondary impermeability has been observed to produce effective cover in the geothermal fields of the Geysers in USA, and Otake in Japan (Ellis, 1967) and this process has been largely discussed and emphasized by Marinelli (1977).

It has been touched earlier that low resistivity anomalies at depth result, to a large degree, from the effect of hydrothermally altered products. An impermeable horizon of considerable thickness can thus form above the reservoir where circulation of fluids occurs. It is proposed that the higher resistivity layer (layer 4, Fig. 13) which overlies the deeper low resistivity layer represents a substantial cover for the convective loss of fluids and heat from the deep reservoir.

The effect of self-sealing also affects fault fractures which otherwise are highly permeable. It is only along faults where renewal of activity is evidenced that this phenomenon is decreased and thermal manifestations are encountered, as in the case of the Chokare fault. Even here it is observed that self-sealing has occurred in previous outlets which are no more discharging fluids.

Therefore, the problem of the cover formation which is lacking in the near-surface rocks is provided quite evidently by low permeability hydrothermally altered layer having a probable thickness of about 200 m, overlying the deep reservoir.

## 7. Conclusions and Recommendations

Eventhough still insufficient, all the available data collected and described in the present study indicate that the NW Lake Abaya area has all the necessary characteristics for the existence of an exploitable geothermal field of high enthalpy. The most promising portion of this area, at least on the basis of the presently available data, extends for about 8 km from the NW shore of the lake and it covers an area estimated in about 45 $km^2$. A reservoir system with an estimated temperature of 200°C and probably higher seems to exist at a depth comprised between 700 and 1300 m. The general structural, volcanological and hydrogeological pattern of this area suggests that both the magmatic heat source and the groundwater circulation supplying the reservoir, might be of great regional importance.

As indicated by a vertical electrical sounding, the top of the reservoir should be covered by an impermeable layer about 200 m. thick formed either by direct hydrothermal alteration or by ancient climatic weathering of the scoriaceous and/or other possible interbeded pyroclastic layers within the Tertiary basaltic trap series, or by both.

The different physico-chemical characteristics of the hot springs found along the Chokare fault, probably reflect different degrees of mixing between deep high temperature fluids and a surfacial water table whose existence is suggested by electrical resistivity, to be at a depth of about 200 m. Among all these thermal manifestiations, only spring 6 reflects a direct origin from a deep geothermal reservoir. Since this spring is only some hundred metres away from all the others, its peculiar uncontaminated character could be better understood if the existence of an important discontinuity of probable tectonic origin located at a certain depth, is postulated. Such a discontinuity could be represented by a vertical fracture with a transverse trend (approx. NW-SE) relative to that of the Chokare fault (NNE-SSW) and not visible on surface either as a tectonic line or as an alignment of thermal manifestations because covered by the recent impermeable volcanic products. Through this fracture at depth and through the Chokare fault near the top part the fluids coming from the deep geothermal reservoir could reach the surface fast and uncontaminated (spring 6), while another portion of the same fluids could infiltrate horizontally into the surficial aquifer, therefore, reaching the surface, still along the Chokare fault but after more complicated paths and showing different degrees of contamination (all the other springs). The results of the dipole-dipole survey seem to confirm the existence of such transverse structure below the surface(see Fig.13) in the vicinity of spring 6 and possibly coinciding with it.

The present conclusions must be considered as preliminary because for a complete understanding of the geothermal system in this area, further detailed investigations are neeeded. These should include the following:

1. Geology and volcanology. A detailed photogeological interpretation with emphasis on the different volcanological and structural features should be done followed by a detailed field work. This should allow quite accurate stratigraphic correlations and appropriate sampling of all the possible different cooling units as well as the xenoliths found within all the pyroclastic formations. All the above refers not only to the area described in the present study but to the entire area north of Lake Abaya affected by Quaternary tectonic and volcanic activity. Additional fieldwork mainly for stratigraphic correlations and sampling for possible radiometric dating should also be done outside the area especially to the west and to the NW.

2. Petrology. Chemical analysis for major and trace elements should be performed on all representative samples selected on petrographic basis. This should give a clear picture of the mutual relations between magmatic evolution and tectonic movements in this part of the Ethiopian Rift in order to establish the real importance of the heat source in this area.

3. Hydrogeology. Detailed geological,investigations should be undertaken especially within the areas of the Bilate and Hamassa river basins. This should allow a better understanding of the amount and

mechanism of regional and local recharge as well as the groundwater circulation pattern.

4. Geochemistry. Compliments of water and gas sampling for geochemical analyses are absolutely necessary on all the known surface manifestations including the steaming grounds in the Salodere-Hoko domes area, never collected before. There are, in fact, quite important discrepancies among the existing geochemical data performed by the different operators. The importance of having reliable geochemical data is beyond any discussion.

5. Geophysics. It is absolutely necessary to extend the electrical resistivity survey with a convenient number of vertical electrical soundings (VES) towards the Salodere-Hoko domes area as well as in the Chokare fault area and in particular in the vicinity of spring 6. Together with this, magnetometry and gravimetry could contribute to get the necessary clear picture of the extension and geometry of the geothermal reservoir at depth. On the basis of the results obtained mainly from points 1 and 2, the geophysical survey could also be extended to areas other than that comprised between the Chokare fault and the Salodere-Hoko domes.

6. Drilling. A convenient number of shallow bore holes adequately scattered could be drilled in order to get informations on the near-surface stratigraphy, lithology and petrography, groundwater geochemistry and piezometry and on the geothermal gradient of the whole area.

Only with the above multidisciplinary work conveniently coordinated and performed according to an adequate time schedule, it will be possible to establish a definite geothermal model for the whole area north of Lake Abaya and in particular for its northwestern portion. Only in such a way it will be possible to indicate the precise drilling sites for deep geothermal production wells and their depth, in order to consistently decrease the risk of unsuccess and consequently to recover the maximum benefit from the investments the Ethiopian Government should necessarily employ for exploitation of this natural resource which is essential for the socio-economic development of the country in the near future.

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# DECLARATION

I, the undersigned, declare that this thesis is my work and that all sources of material used for the thesis have been duly acknowledged.

Gezahegne Yirgu

Addis Ababa, July 1980