

THE CHEMISTRY OF GEOTHERMAL FLUIDS IN GEOTHERMAL AREAS OF  
THE LAKES DISTRICT, ETHIOPIAN RIFT VALLEY

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ABSTRACT

Data on the chemical composition of water and gas as well as isotopic data from five geothermal areas in Lakes District, Ethiopia, were integrated and studied for better understanding of the geothermal systems. The waters are mostly of the sodium bicarbonate type, with near neutral pH. Intermediate to acidic volcanic rocks dominate in all the areas studied. Mixing of the hot water with cold waters is common in the upflow. Partial re-equilibration has occurred subsequent to mixing and as a result the solute geothermometers indicate relatively low temperatures. The gas geothermometers tend to indicate higher subsurface temperatures than the solute geothermometers.  $\text{CO}_2$ -temperatures exceed  $300^\circ\text{C}$  for all the fields (no fumarole in Shalla) and  $\text{CO}_2/\text{H}_2$ -temperatures tend to exceed  $200^\circ\text{C}$ . Due to the effects of condensation,  $\text{CO}_2$ -temperatures tend to be high, but as a result of reactions in the upflow involving  $\text{H}_2$   $\text{CO}_2/\text{H}_2$  temperatures are expected to be low. The  $\text{SiO}_2$ -carbonate mixing model was found to indicate better temperature estimates of the hot water components of the geothermal areas in the Lakes District compared to the others. The empirically derived temperature relations of aqueous species concentrations and cation/proton activity ratios, based on Icelandic chemical data, fits well for the Lakes District fluids except for ratios involving Mg.

Subsurface temperature in the four geothermal fields may be as high as  $300\text{-}340^\circ\text{C}$  for the Aluto-Langano complex,  $300^\circ\text{C}$  for Corbetti,  $250\text{-}300^\circ\text{C}$  for Wondo Genet and  $300^\circ\text{C}$  for the Abaya geothermal area. There may be an independent heat source for Shalla area with a minimum temperature of  $200^\circ\text{C}$ . The geothermal fluids are calculated to be supersaturated with calcite and close to saturation with fluorite. At depth, they are highly undersaturated with respect to anhydrite.



TABLE OF CONTENTS

	Page
ABSTRACT .....	3
1 INTRODUCTION	
1.1 Scope of study .....	8
1.2 Previous geochemical work .....	9
1.3 Obejective of the study .....	10
2 GEOLOGY AND DESCRIPTION OF THE GEOTHERMAL AREAS IN THE LAKES DISTRICT	
2.1 Regional setting and geology .....	11
2.2 Description of the studied areas: Abaya; Awasa-Wondo Genet; Corbetti; Shalla and Langano .....	11
3 SAMPLING AND ANALYTICAL METHODS .....	15
4 CHEMICAL CHARACTERISTICS OF THE GEOTHERMAL AREAS .....	16
5 GEOTHERMOMETRY	
5.1 Solute geothermometry .....	19
5.2 Solution-mineral equilibria .....	22
5.3 Gas geothermometry.....	24
6 MIXING PROCESSES	
6.1 Evidence for mixing .....	29
6.2 Mixing models .....	32
6.2.1 Silica-enthalpy mixing model .....	33
6.2.2 Silica-carbonate mixing model .....	33
7 SUMMARY .....	36
8 RECOMMENDATIONS .....	38
ACKNOWLEDGEMENTS .....	40
REFERENCES .....	41

Appendix I:	Sampling and analytical methods adopted for geothermal fluids .....	67
Appendix II:	Equations describing the temperature dependence of mineral solubilities .....	68
Appendix III:	Samples of computer printout of the WATCH 2 programme .....	69

#### LIST OF FIGURES

1.	Geological map of the Lakes District .....	45
2.	Comparison between the results of individual solute geothermometers and the mean temperature of all of them .....	46
3.	Relation between carbon dioxide/fluoride concentrations and quartz equilibrium temperature/discharge temperature in the Lakes District geothermal waters ..	47
4.	Relation between sulfate/sulfide concentrations and quartz equilibrium temperature/discharge temperature in the Lakes District geothermal waters .....	48
5.	Relation between cation/proton ratios and quartz/-discharge temperature in the Lakes District geothermal waters .....	49
6.	State of calcite and anhydrite saturation at quartz/-discharge temperature in the Lakes District geothermal waters .....	50
7.	State of fluorite saturation at quartz/discharge temperature in the Lakes District geothermal waters ..	51
8.	D/H and O-18/O-16 variations in thermal and cold waters from the Lakes District .....	52
9.	Relationship between chloride concentrations and boron, O-18, SiO <sub>2</sub> and SO <sub>4</sub> in cold and thermal waters from the Abaya area .....	53

10. Relationship between chloride concentrations and boron, O-18, SiO <sub>2</sub> and SO <sub>4</sub> in cold and thermal waters from the Awasa-Wondo Genet area .....	54
11. Relationship between chloride concentrations boron, O-18, SiO <sub>2</sub> and SO <sub>4</sub> in cold and thermal waters from the Shalla area .....	55
12. Relationship between chloride concentrations boron, O-18, SiO <sub>2</sub> and SO <sub>4</sub> in cold and thermal waters from the Langano area .....	56
13. Silica-enthalpy mixing model .....	57
14. Silica-carbonate mixing model .....	58

#### LIST OF TABLES

1. Chemical composition of waters in the Lake Abaya area.	59
2. Chemical composition of waters in the Awasa-Wondo Genet area .....	59
3. Chemical composition of waters in the Shalla area ....	60
4. Chemical composition of waters in the Langano area ...	60
5. Isotopic composition of waters in the Lakes District geothermal areas .....	61
6. Calculated temperatures from solute geothermometers ..	62
7. Temperature functions for solute geothermometers .....	63
8. Gas analyses results from Langano, Corbetti and Abaya areas .....	64
9. Estimated temperatures from gas geothermometers for Langano, Corbetti and Abaya areas .....	65
10. Temperature functions for gas geothermometers .....	66

## 1 INTRODUCTION

### 1.1 Scope of work

Ethiopia was the second country in Africa to start geothermal exploration for power development. Scientific and technical know-how is essential to explore and utilize this energy resource. Training in countries with experience in geothermal exploration, development, and utilization is probably the best resolution to build up relevant know-how. In line with this approach the author was accepted as a United Nations University Fellow in the 1985 UNU Geothermal Training Programme in Iceland and specialized in the chemistry of thermal fluids.

Introductory lectures covering the various scientific, engineering, and economic aspects in geothermal exploration and exploitation were given. In addition, study tours were arranged to see both high- and low-temperature geothermal fields in Iceland. Greenhouses, factories and farming places which are directly inter-related with geothermal utilization were also visited.

The specialized training in the chemistry of thermal fluids included water and steam sampling from natural thermal manifestations and production wells in high- and low-temperature fields, analyses of water and steam samples, computer work for speciation calculations, lectures on chemical thermodynamics as basis for geochemical interpretation, interpretation methods for geochemical data based on exercises and problems and computer approach to the interpretation of chemical data. The specialized training was performed mainly under the supervision of Dr. Stefan Arnorsson of the University of Iceland, but also Dr. Jon Orn Bjarnason of the National Energy Authority and Dr. Einar Gunnlaugsson of the Reykjavik Municipal District Heating Service.

This report describes the author's research project which was a part of the training programme. The project was carried out during the last two months of the training period. Data from reports describing previous scientific work in Lakes District, Ethiopia were used. Chemical and



isotopic data from water and steam (including chemical data of Shalla cold spring) were taken from UN (1973), Glover (1976), and Craig (1977), respectively.

The chemical data were re-arranged to use the computer programmes of Arnorsson et al.(1982). Hence total carbonate species were calculated and reported as carbon dioxide and  $\text{HBO}_2$  as B.

## 1.2 Previous geochemical work

Chemical data on hydrothermal waters in the Ethiopian Rift and probable deep water temperatures deduced from silica and Na-K geothermometers were reported by UN (1973). Glover (1976) reported gas analyses results and gas-gas equilibrium temperatures ( $t_{\text{CH}_4}$ ,  $t_{\text{NH}_3}$ ). Isotopic and chemical data including the sulfate-water isotopic temperatures in and around the Rift is reported by Craig (1977). Furthermore, geochemical work of the Langanu geothermal area which include the first four deep exploratory wells were described by Melaku Abebe (1983) and Negussie Mekuria (1983).

There are considerable differences in the data from the same springs in the reports of UN (1973) and Craig (1977). Craig's statement concerning this is that "the estimates of subsurface temperatures cannot be considered useful until the question of reality of these compositional differences and/or the reliability of the two sets of data can be resolved." The discrepancy may be due to poor analytical precision. The present author considers that the compositional variation affects little the geothermometry results.

Three areas have been selected for exploration and development in the Lakes District, Langanu in the north, Abaya in the south and Corbetti in the middle of the district. In all of these fields subsurface temperatures of more than  $180^\circ\text{C}$  have been estimated (UN, 1973; Glover, 1976; Melaku, 1983). Drilling started in one of these fields (Aluto-Langanu) in 1981. Eight deep exploratory wells were completed in 1985. The maximum temperature encountered in a drillhole is  $318^\circ\text{C}$  in LA-6. Five holes are productive (water dominated). Detailed exploration involving geologi-

cal, geophysical and geochemical work is still in progress in the remaining two fields.

### 1.3 Objectives of the present work

Previous geochemical studies in the Lakes District have been focused mainly on the estimation of subsurface temperatures. However, the interpretation did not consider the effect of mixing of the hot water in the upflow on the results. Geothermometry results are anomalous for mixed waters. Therefore, it is necessary to evaluate if mixing has occurred. Recently proposed gas and cation geothermometers have been applied to the existing geochemical data to assess subsurface temperatures. Gas geothermometers are especially useful for an area such as Corbetti where the thermal manifestations are restricted to fumaroles and steaming ground.

So far limited attention has been paid to the quantitative evaluation of the solute-mineral equilibria in the geothermal systems. It is the objective of this report to integrate the available geochemical data (Tables 1, 2, 3, 4, 5 and 8), and

- (1) identify and evaluate the mixing processes by chemical means and mixing models;
- (2) apply newly calibrated chemical geothermometers to predict subsurface temperatures;
- (3) study solution-mineral equilibria.

## 2 GEOLOGY AND DESCRIPTION OF GEOTHERMAL AREAS IN THE LAKES DISTRICT

### 2.1 Regional setting and geology

The Ethiopian Rift Valley is part of a major tectonic structure that extends for more than 6,000 km from the Middle East in the north to Mozambique in the south, known as the East African Rift System (Fig. 1). The great majority of this system, including the Ethiopian Rift, is the surface expression of diverging lithospheric plate boundaries. A regional heat flow anomaly extends for more than 1,000 km within the Ethiopian Rift (UN, 1984).

The Lakes District is located south of Addis Ababa in a relatively narrow part of the Ethiopian Rift Valley. Its elevation extends from 1,230 m at Lake Shamo in the south to about 1,800 m at the Awash River watershed in the north. Structurally the Lakes District Rift is a broad graben in which Tertiary rocks have been down faulted and filled with Quaternary sediments (UN, 1973). Lakes Shamo, Abaya, Awasa, Shallo, Chittu, Shalla, Abayta, Langano, Zwai, and Gelilla are all found in the Lakes District.

### 2.2 Description of the studied areas: Abaya, Awasa-Wondo Genet, Corbetti, Shalla and Langano

This report uses the same index numbers for sampling sites as was done in the 1973 UN report. The index numbers for Lake Abaya (including Graha-Quhe springs east of Awasa) are NB-37/6-. For Lake Awasa-Wondo Genet, Corbetti, Lake Shalla and Lake Langano areas the index numbers start with NB-37/2-. Geological map of the areas including thermal manifestations is shown in Fig. 1.

#### Lake Abaya area

Lake Abaya is located at 1386 m elevation in the rift floor south of Lake Awasa and north of Lake Shamo, 6°15'N; 37°55'E. Thermal manifestations (fumaroles and springs) are mainly concentrated on the north and northwest shore of the

lake. All of the springs are close to the water level of Lake Abaya and the Bilate River. They occur on the western marginal rift faults near the center of the graben. Many of them are closely related to centers of rhyolitic volcanism (UN, 1973).

The spring discharges range from very small to 20 l/s with temperatures between 37° and 95°C. Spring 6 deposits siliceous sinter while most of the others deposit limonite very near to their outlet. Due to the low amount of inflow in the recent years Lake Abaya receded from its 1980 level and several new boiling springs were exposed along a line south of spring 6 which are compositionally similar to it. Later, the lake recovered to its original level (UN, 1984).

#### Lake Awasa-Wondo Genet area

Lake Awasa (1,780 m) occupies an unusual tectonic basin completely enclosed by faults south of Corbetti volcanic center (UN, 1973). Wondo Genet is located east of Awasa, southeast of Shashemene very near to Lake Shallo. All the springs are located east of Lake Awasa. Cold wells for which chemical data are available occur in Awasa town near the eastern shore of Lake Awasa. Wondo Genet (40) springs deposit travertine and springs 38 and 39 (not analyzed) deposit limonite close to their vents (UN, 1973). Shallo springs (52, 48) are located by the northeast corner of Lake Shallo. These are the hottest in the area (96°C) but with low flow rate. The author recently visited the lately formed hot springs in this area. The temperature recorded at the edge of a pool was 94°C. Higher temperatures are expected in the center where surface cooling is negligible. These springs are the most vigorously boiling ones in Wondo Genet formed after the earthquake in 1984.

#### Corbetti Caldera

Corbetti Caldera is located about 38°27' E, 7°10' N in the Lakes District Rift. The maximum altitude is about 2300 m (Chebbi volcano) and the flat plains are at about 1700 m. Corbetti caldera, a Quaternary volcano in the rift, has

extensive hydrothermal manifestations. The area comprises sedimentary and volcanic rocks (Elias, 1984).

Corbetti (meaning obsidian) caldera has three volcanoes, namely Chebbi(SE), Urgi(center), and Danshe (N). Fumaroles, steaming and hot ground are very common in these volcanoes. Steaming ground extends to the north outside the caldera.

#### Lake Shalla area

Lake Shalla, 7°25'N; 38°30'E; is the deepest lake in the district (over 250 m). Except for minor basalts all rocks exposed in the Shalla region are rhyolitic (predominantly ignimbrites and pumice breccias) and lacustrine sediments derived from them. The most recent volcanic eruption was explosive and produced pumice from centers between Lake Shalla and Abayata (UN, 1973).

Hot springs are distributed along the eastern, southern and western shores of the lake. The eastern springs are the warmest in the area and discharge clear water as far as 100 m from the lake. Salt deposition is associated with springs 90 and 91. Springs 87 and 88 emerge from mud. At spring 29, no sinter is deposited, but algae grows in the 1.25 l/s overflow. One km south of spring 29, springs collectively numbered 30, emerge from dark mudstone overlain by superficial alluvium (UN, 1973).

In between Corbetti Caldera and Lake Shalla there is about 1 km diameter lake, Chittu which is 1.5 km south of the southern shore of Lake Shalla. Two groups of springs have been recognized, those emerging at the southeastern part and those discharging clear water at the northeastern shore of the lake. The discharge is about 6.6 l/s at the southern part and 3.3 l/s at the northern point with moderate temperatures (51-60°C).

Lake Langano area

Lake Langano (1586 m) is located a few km east of Lake Abayata and Lake Shalla Park. Lake Langano, Aluto Volcanic Center, and Zwai (north of Lake Langano) all lie within a north-northeast aligned tectonic depression bounded to the west by Langano Fault and to the east by a series of faults which form the eastern rift escarpment (UN, 1973).

Hot springs in this area are mostly confined to the northeastern shores of the lake. Vigorous springs in the area are found in the Geyser Island (10-13). The temperature is near boiling (96.5°C) in spring 10 with flow of 11.6 l/s. The name Geyser is probably given to this spring. Goetz (a German settler since 1902 in the area) reported that a geyser suddenly developed in 1906 at the time of the Langano earthquake. He also mentioned that the geyser erupted to a height of about 25-30 m about once every 30 seconds. At present it is a boiling hot spring.

A maximum temperature encountered through deep exploratory drilling in Aluto-Volcanic center is 318°C at about 2000 m in the 2203.4 m deep well, LA6.

### 3 SAMPLING AND ANALYTICAL METHODS

This report is based on data of previous workers (see section 1.1). Analytical methods adopted are described in the respective reports. Very few springs were analyzed in all of the investigated areas compared to the availability of thermal manifestations. More data would have been of advantage for the application of mixing models. The information given for water sampling is insufficient. It is very difficult to predict whether the samples were treated or not, especially for silica. Filtering, dilution, concentration, and/or acidification processes are not described.

It is essential to analyse unstable constituents ( $\text{CO}_2$ ,  $\text{H}_2\text{S}$ , pH) at the sampling site right after collection from raw-untreated sample. Samples for Ca, Mg, Na, and K should be filtered and acidified. If the sulfide content is high it is possible that oxidation into  $\text{SO}_4$  occurs. Therefore, it is necessary to precipitate sulfide by adding  $\text{Zn}(\text{CH}_3\text{COO})_2$  solution to a sample intended for  $\text{SO}_4$  determination. Samples for  $\text{SiO}_2$  should be diluted or treated by alkaline solution prior to analysis to avoid silica polymerization which occurs if total dissolved silica exceed about 100 ppm. Appendix (1) summarizes sample treatment and analytical methods adopted for major elements in geothermal fluids in Iceland.

#### 4 CHEMICAL CHARACTERISTICS OF THE GEOTHERMAL AREAS

The location of all the samples is shown in Fig. 1. Tables 1-5 show the chemical and isotopic data of selected thermal and cold waters in the Lakes District used for the present study.

Generally, thermal waters in the Lakes District are high in bicarbonate and fluoride. Sodium is the predominant cation followed by potassium. The pH is slightly above neutral, except for few springs in Shalla. The waters are, therefore, classified as dilute near neutral sodium bicarbonate waters. There are also springs which discharge acid sulfate waters. They are steam heated surface waters, the low pH being due to oxidation of  $H_2S$  into  $SO_4^{2-}$ . Waters high in bicarbonate often form by mixing of high temperature waters with surface water. The high fluoride most likely results from relatively high fluoride in the associated acid volcanics.

##### Lake Abaya area

The Abaya spring waters can be divided into two groups on the basis of their composition and distribution. Springs which are located nearest to the northwestern shore of the lake, i.e. 6, 8, 15, and 16 fall into one group and those which are further north (about 33 km from spring 16) constitute the other group. This latter group (19, 20, 22 and 24) is characterized by high F and carbonate and low Cl relative to  $SO_4$  as well as high boron content, at least in spring 22, suggesting that they may be steam heated. This was recognized in the UN report (1973).

The first group of springs is very important in the area. Spring 6 which is nearest to the lake and the most vigorous one has the highest discharge temperature and the highest concentrations of Cl,  $SiO_2$  and total carbonate in the Abaya area. The oxygen shift in this spring water is significant compared to others. Springs 8, 15, and 16 have low to moderate temperatures (42-65.5°C), lower  $SiO_2$  and Cl contents but are higher in bicarbonate, Ca and Mg concen-



trations. These latter spring waters are assumed to be partially steam heated meteoric waters (see sec. 6.1).

#### Awasa-Wondo Genet area

Springs 4, 40, and 52 emerge on a swampy plain and are relatively mineralized compared to the springs on the eastern escarpment (44 and 46). The temperature of the spring discharges is between 43°C and 96°C. Lake Awasa and cold wells in Awasa are evaporated waters (see chapter 6). In general, these waters are low in Cl (< 129 ppm), boron and fluoride (except 4 and 52) but with considerable concentrations of Ca and Mg. Spring 40 appears to be unique in the group. It has the highest Cl, SO<sub>4</sub>, bicarbonate and Cl/F ratio but the lowest Na/Li ratio in the district.

#### Lake Shalla area

Springs in this area emerge at the eastern (29, 30, 31, 35, 36,), southern (90, 91), and the southwestern shore of Lake Shalla (95, 96).

The springs by the eastern shore have similar cation/proton ratios, with pH ranging from 8.35 to 9.7. Spring 30 is more mineralized and apparently somewhat degassed compared with other springs in the group. The eastern springs show a positive Cl-temperature relationship. By contrast, an inverse relation between SiO<sub>2</sub> and Cl is observed in the Shalla springs. The analyzed silica concentrations correspond closely to amorphous silica saturation at 25°C. Although not proved, these analyses are suspect to error. It is possible that the analyzed silica represents monomeric silica at room temperature and not total dissolved silica in the samples.

Springs 90 and 91 have high Cl, low Na/K, low Cl/carbonate ratio and moderate temperatures (62 and 70°C). These springs are very close to the lake shore (less than 1.5 m). The pH of spring 91 (10.1) is very similar to the pH of Lake Shalla (10.15), the most saline lake in the district

(3030 ppm). This suggests that these waters are steam heated lake water.

South Shalla springs (87, 88) have similar chemistry as Chittu spring waters (60, 65) the former being slightly more mineralized. These springs are characterized by high  $\text{SO}_4$  for their Cl, low silica, high carbonate and appreciable concentration of Ca and Mg. This suggests that the Chitu springs may contain steam heated shallow meteoric water.

#### Lake Langano area

Springs by the shore of the northern bay of the lake (2, 3 and 84) have low flow rates and moderate temperatures (61-67°C). The pH is near neutral (8.1-8.3) and the waters are relatively high in Ca, Mg, and with high Cl/ $\text{SO}_4$  ratio.

The Bole fault springs (5,8A) have high boron, high temperature (92°C and 94°C), and low flow rate, low Cl, and low Cl/ $\text{SO}_4$  ratio. In spite of their distance from the source (Aluto volcanic center), they are considered to be steam heated.

Springs in the Geyser Island (10,12) are slightly alkaline, low in Ca and Mg, high in Cl and have low Cl/ $\text{SO}_4$  ratio. Slight oxygen shift was detected in spring 11 (Craig, 1977). These are the least diluted springs in the area.

Spring 16, the coolest and the least mineralized one in the area, has the highest flow, and the highest Ca and Mg concentrations in the group. This spring has a high cold meteoric water component.

Zwai springs (20,23) on the other side of the Aluto Volcanic Center are characterized by moderate temperatures (60°C, and 78°C), low discharge rates and low Cl (31 and 95 ppm). The Cl/ $\text{SO}_4$  ratios lie in between those north of the bay and the geyser springs.

## 5 GEOTHERMOMETRY

Tables 6 and 9 show the calculated temperatures from solute as well as gas geothermometers for Lakes District waters and steam. The equations used for the solute and gas geothermometers are listed in Tables 7 and 10, respectively. The relationship between individual solute geothermometers and the mean of them all is shown in Fig. 2. The relationship between acid molecules concentration and cation/proton ratios and quartz/discharge temperature is shown in Figs.3-5.

The use of chemical geothermometers involves the assumption that equilibrium is attained between fluid and a particular mineral assemblage in the reservoir and that re-equilibration in the upflow is insignificant. The rock type, temperature, kinetics and rate of dissolution of various chemical constituents from the rock determine which geothermal minerals will form, and how closely this open chemical system approaches equilibrium each time. Different reactions may occur in an ascending water at different rates. The apparent last temperature of equilibrium may thus be different for different chemical geothermometers (Arnorsson et al.,1983a; Fournier, 1977). Chemical re-equilibration is favoured when water temperatures are high initially, when rates of water movement towards the surface are slow, when residence times in reservoirs at intermediate and shallow depths are relatively long, and when the water flows through chemically reactive rocks (Fournier et al.,1974).

### 5.1 Solute geothermometry

Arnorsson et al.(1983b) used data on selected drillhole fluid compositions (Iceland) to calibrate several activity ratios ( $a_{Na^+}/a_{H^+}$ ,  $a_{K^+}/a_{H^+}$ ,  $(a_{Ca^{2+}})^{1/2}/a_{H^+}$ ,  $(a_{Mg^{2+}})^{1/2}/a_{H^+}$  and acid molecule concentrations ( $H_2CO_3$ ,  $H_2SO_4$ ,  $H_2S$ ,  $HF$ ,  $H_4SiO_4$ ) against temperatures. An expansion of such calibration involving 10 solute geothermometers is presented by Arnorsson and Svavarsson (1985). An attempt has been made to apply the calibrated geothermometers for waters in the Lakes District.

The equilibrium temperature of various solute geothermometers have been calculated. The reference temperature, quartz equilibrium, at which the calculations were performed was selected on the basis of having the least deviation from the mean temperature (more likely to be the equilibrium temperature). The silica content and alkali ratios may change as the water slowly rises owing to decreased solubilities at lower temperature and water-rock reactions. Silica temperatures often show quicker response to cooling in upflow zones. The Na/K temperatures are not affected by dilution, and evaporation. On the other hand dissolution following mixing tends to cause high Na-K temperatures.

When silica precipitation occurs in the upflow and when waters have appreciable concentration of Ca, the Na-K-Ca geothermometer may give more reliable results than the SiO<sub>2</sub> and Na/K geothermometers. Arnorsson et al. (1983a,b) showed that each of the two cation ratios which constitute the Na-K-Ca geothermometer (Na/K and (Ca)<sup>1/2</sup>/Na) are determined by water temperature alone. Therefore, for equilibrated geothermal waters, which have cooled by conduction in upflow zones, the Na-K-Ca geothermometer may give a better estimation than the Na/K geothermometer as the (Ca)<sup>1/2</sup>/Na appears to respond faster to cooling than the Na/K ratio. Changes in concentration resulting both from boiling and mixing with cold, dilute water will affect the Na-K-Ca geothermometer. Boiling generally will result in high Na-K-Ca temperatures because of calcite precipitation leads to removal of aqueous Ca<sup>+2</sup>.

Mixed waters tend to yield low H<sub>2</sub>S, Mg-K and Na-Li temperatures but high Na-K temperatures. The geothermometers involving Li, Rb and Mg often yield temperatures differing much from the other geothermometers. Arnorsson and Svavarsson (1985) explained this as being partly due to the low levels of these metals (near detection limit by flameless A.A) for Icelandic waters used for calibration. In some instances the Na-Li geothermometer results are similar to the CO<sub>2</sub> gas geothermometry values.

For the Lakes District waters the temperatures of silica (quartz),  $H_2S$ , and  $H_2SO_4$  are lower than the mean whereas the  $CO_2$ , Na-K-Ca, Na-Li and HF temperatures are higher (Fig. 2). Na/K and Mg-K temperatures are highly fluctuating. The low temperatures of silica,  $H_2S$ ,  $H_2SO_4$ , Mg-K and higher values of Na/K temperatures are explained by precipitation of silica and reactions following mixing. When high temperature hot water, which is rich in  $CO_2$  mixes with cold underground water, the mixture will initially be acid, but upon reaction with the rock the pH will increase and  $CO_2$  will be converted to  $HCO_3^-$ . Leaching of K gives high Na/K temperatures. In contrast leaching of Mg results in lower Mg-K temperatures. In most cases, the Mg-K temperatures are slightly above the measured surface temperatures suggesting intensive leaching/mixing in the upflow.

Almost all the samples plot close to the CaH equilibrium curve at quartz equilibrium temperature (Fig. 5). The concentration of the HF ion pair is slightly higher than expected from the HF "equilibrium" curve at the quartz equilibrium temperature. The reason may be that the HF equilibrium curve is derived from data in basaltic terrain in Iceland but the Lakes District geothermal systems occur in acidic volcanics. Thermal waters associated with such rocks tend to equilibrate with fluorite.

At the measured discharge temperatures samples from all geothermal areas have  $Na^+/H^+$ ,  $K^+/H^+$ , and  $(Mg^{+2})^{1/2}/H^+$  ratios both higher and lower than expected at equilibrium (Fig. 5). At the quartz equilibrium temperature the same ratios always plot above the equilibrium curve. This indicates substantial re-equilibration for Mg, Na, K and/or H during cooling in the upflow.

The concentrations of  $H_2S$  and  $H_2SO_4$  are above the equilibrium curve at discharge temperatures but slightly below it at quartz equilibrium temperatures indicating, as for the cations, partial re-equilibration in the upflow. The concentrations of  $H_2CO_3$  are higher than indicated by the equilibrium curve both at the measured discharge temperature and quartz temperature.

The most diluted springs (16 in Abaya, 44 in Wondo Genet, 16 in Langano and 23 in Zwai) plot far from the equilibrium curves. This is because of precipitation of minerals from the waters, leaching from the rock, oxidation and/or mixing processes in the upflow zones.

The somewhat large differences between the different solute geothermometers (Table 6) may have resulted from mixing in the upflow. However, if such mixing has occurred it seems likely that substantial re-equilibration has occurred subsequent to mixing. Evaluation of mixing processes are considered in chapter 6.

## 5.2 Solution-mineral equilibria

Solution-mineral equilibrium studies are one of the best approaches to interpret fluid chemistry. Application of chemical geothermometers is indeed based on the assumption that solution/mineral equilibria are attained in geothermal systems.

The conditions for equilibrium in multiphase systems are described by the Gibbs phase rule. It can be demonstrated that the number of compatible chemical components is equal to the number of phases in the system. Thus, the phase rule may be written in a simplified form as

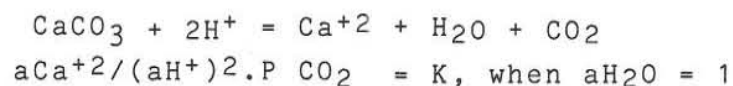
$$F = M + 2$$

where  $F$  is the number of independent variables needed to define the system completely and  $M$  the number of mobile components. 2 indicates temperature and pressure. Chloride is the only major mobile component in most geothermal waters. The effect of pressure on solution-mineral equilibria in the range occurring in geothermal systems (1-200 bars) is found to be small (Helgeson et al., 1978; Ellis and McFadden, 1972; Arnorsson et al., 1983a). It follows, therefore, that the number of variables required to define the major element chemistry of geothermal waters at equilibrium are two, chloride and temperature.

Physical processes such as boiling and cooling as well as the rate of leaching of various components from the primary rock constituents and the rate of precipitation of alteration minerals tend to shift the geothermal system from equilibrium.

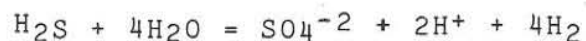
The state of saturation of some geothermal waters with respect to calcite, anhydrite, and fluorite was calculated with a computer programme (Arnorsson et al, 1982) with reference to the measured surface temperatures and quartz temperatures (Fig. 6 and 7). The results indicate calcite saturation at discharge temperatures. Significant anhydrite undersaturation is observed both at discharge and quartz equilibrium temperatures. Some of the waters calculate to be close to fluorite saturation but others are undersaturated at the quartz equilibrium temperatures. No correlation can be seen between the degree of saturation and temperature. At discharge temperatures both supersaturation and undersaturation is observed (Fig.7). It has been found in many geothermal fields in acid volcanic rocks that equilibrium between fluorite and solution is attained in the reservoir. Mixing with cold water will upset equilibrium and this may be the cause of departure from equilibrium for the Lakes District waters.

It has been demonstrated at a given temperature, independent of salinity, that the ratio  $(a_{Ca^{2+}})^{1/2}/a_{H^+}$  is constant for geothermal waters (Arnorsson et al, 1978; Palmason et al., 1979 ). It follows then that a fixed  $P_{CO_2}$  value corresponds to calcite saturation at a given temperature.



All the waters considered in this study are supersaturated with calcite at the quartz reference temperature. Except for a few spring waters from Awasa-Wondo Genet area, they are also supersaturated with respect to calcite at the surface. An average deviation from the saturation curve in terms of  $\log Q$  is 1 and 0.5 at the quartz and the surface discharge temperature, respectively. The apparent supersaturation at discharge temperatures may be due to degassing, either prior to or subsequent to sampling.

Whichever reference temperature is selected (quartz, measured, Na/K) Lakes District waters calculate to be highly undersaturated with respect to anhydrite. The degree of undersaturation increases with decreasing chloride. Shalla 90, 91 are exceptional because of contamination by the saline lake water. This relation was also seen in Icelandic waters (Arnorsson et al., 1983a). The systematic trend towards increasing anhydrite undersaturation with falling temperature and decreasing salinity may be related to the control of sulfate activity through the reaction



and the buffering effects of iron minerals on the partial pressures of hydrogen and hydrogen sulfide ( Arnorsson et al., 1983a ).

The waters are quartz and chalcedony supersaturated at the discharge temperatures resulting from cooling or mixing of the geothermal water in the upflow. The average deviation from the equilibrium curve in terms of log Q is 0.6 and 0.3 for quartz and chalcedony, respectively.

### 5.3 Gas geothermometry

The gas content in geothermal systems is controlled by temperature dependent equilibria with alteration minerals in the reservoir rock (Giggenbach, 1980; Nehring and D'Amore, 1981, 1984; D'Amore and Truesdell, 1980; Arnorsson et al., 1983a; Arnorsson and Gunnlaugsson, 1985). Various equations for gas geothermometers have been proposed (D'Amore and Panichi, 1980; Nehring and D'Amore, 1981, 1984; Arnorsson et al., 1983b; Arnorsson and Gunnlaugsson, 1985) recently.

CO<sub>2</sub>, H<sub>2</sub>S, CH<sub>4</sub>, H<sub>2</sub>, N<sub>2</sub>, and NH<sub>3</sub> constitute the most abundant gases in geothermal systems. The amount of these gases in the steam phase depend on the original gas composition of the aquifer, the distribution coefficients between steam and water phases and the steam fraction. The proposed



temperature functions include both gas concentrations and gas ratios and when applying all the geothermometers together a valuable information can be obtained on subsurface temperature and condensation/steam-separation in the upflow as well as reactions.

The gas geothermometers which are based on gas ratios will give the most reliable results when condensation in the upflow significantly affects the gas concentrations in the steam and reactions with wall rock minerals have relatively less effect on the gas ratio/ratios, whereas geothermometers which use gas concentrations in fumarole steam are advantageous over the gas ratio geothermometers when steam condensation or phase separation in the upflow have less effect than reactions (Arnorsson and Gunnlaugsson, 1985).

In active volcanic vents the cooling of gases takes place quite rapidly and the gas reactions do not adjust completely to the lower temperatures resulting in higher calculated equilibrium temperatures (from gas analysis of the sampled discharge) than the collection temperature, but somewhat lower than the deep temperatures (Glover, 1976).

Gas analysis data (Glover, 1976) were used to apply the newly calibrated gas geothermometers for Lakes District geothermal areas (Table 8). The excess  $N_2$  was calculated assuming all  $O_2$  in the samples is atmospheric. The gas analyses results are tabulated in Table 8 and the estimated equilibrium temperatures using the gas geothermometers of Arnorsson and Gunnlaugsson (1985) are listed in Table 9.

#### Lake Langano area

Data for eight fumaroles in the Langano geothermal field are shown in Table 8. They include Aluto B (NE), Finkilo (S), and Bobesa (E) fumaroles, all located inside the Aluto Caldera, whereas Auto and Hulo (W), Kure, Gebiba and Feature 18 (S) are all outside the caldera, (Fig. 1).

There is a considerable variation in the estimated temperatures by the different gas geothermometers. The CO<sub>2</sub> estimates (275-357°C) are higher than the estimated temperatures from the other gas geothermometers. However, the maximum temperature encountered through deep exploratory drilling inside the caldera is in the range given by the CO<sub>2</sub> geothermometer (318°C). As shown in Gebiba fumarole (291-300°C), CO<sub>2</sub>-N<sub>2</sub> and H<sub>2</sub>S-H<sub>2</sub> temperatures compare well within +/- 9°C. The available data are limited so comparison for the other fumarols is not possible. H<sub>2</sub>S temperatures are at maximum at Aluto B, 239°C with an average of 220°C. The temperature estimated from H<sub>2</sub> and CO<sub>2</sub>-H<sub>2</sub> gas geothermometers are lower than that of CO<sub>2</sub> but higher than the H<sub>2</sub>S temperatures (Gebiba Fumarole). Condensation followed by removal of H<sub>2</sub> is the cause of the discrepancy. Oxidation of H<sub>2</sub>S is more pronounced than that of H<sub>2</sub> in the upflow. The CO<sub>2</sub>-N<sub>2</sub> results are inconsistent in most cases whether correction has been made for excess N<sub>2</sub> or not.

The CO<sub>2</sub>-H<sub>2</sub>S, CO<sub>2</sub>-NH<sub>3</sub>, H<sub>2</sub>-NH<sub>3</sub> ratios and the results from gas geothermometry indicate that Finkilo and Aluto B are closer to a major upflow zone than the fumaroles at Auto and Hulo. Finkilo and Aluto B fumaroles are located on opposite sides of the caldera (NW and S), so presumably the upflow would be within the caldera. This is not in line with interpretation in Glover's (1976) report, but in line with the confirmed result through drilling. The estimated temperatures from T CH<sub>4</sub> (180°C) and T NH<sub>3</sub> (188°C) are similar to that of the solute geothermometers. However, the agreement between the two should not be taken as a good indication of subsurface temperatures since mixing results in low estimates by the solute geothermometers (see chapter 6). The sulfate-water isotopic temperatures show more or less similar results, i.e. 314°C and 346°C for spring 5 and 12 assuming conductive cooling, and 256°C and 280°C assuming cooling by steam loss, respectively (Craig, 1977). It should, however, be noted that mixing which leads to oxidation of H<sub>2</sub>S causes sulfate-water isotopic temperature to be high.

### Lake Abaya area

The thermal manifestations in Lake Abaya area constitute widely scattered hot springs and fumaroles. Abaya F (Abaya fumarole) and Duguna fumaroles (about 30 km north of the Lake) have been used to evaluate subsurface temperatures. Abaya F, located very near to spring 6 and the Lake, is the most vigorous sampled in the Lakes District and the only one at which the "puggy clay" was observed usually associated with sulfuric acid attack caused by oxidation of H<sub>2</sub>S (Glover, 1976).

The CO<sub>2</sub>, H<sub>2</sub>S and CO<sub>2</sub>-H<sub>2</sub> geothermometers in this geothermal area are the highest in the Lakes District. The average values from CO<sub>2</sub>, CO<sub>2</sub>-N<sub>2</sub> (without correction for excess N<sub>2</sub>), H<sub>2</sub>S-H<sub>2</sub>, H<sub>2</sub> and CO<sub>2</sub>-H<sub>2</sub> gas geothermometers are 344°C, 283°C, 263°C, 251°C, 244°C and 205°C, respectively. The differences between individual gas geothermometers can be explained by condensation or steam separation at elevated pressure and reactions in the upflow. As inferred from the gas geothermometers, the hot water body underneath Abaya area is expected to have a temperature in the range of 300-350°C. Abaya F seems to be closest to the hot water source. This area is characterised by low resistivity anomaly (Ketsela, 1984). The sulfate-water isotopic temperatures for this area shows 325°C assuming conductive cooling (Craig, 1977).

### Corbetti

The thermal manifestations in the Corbetti Caldera (Fig. 1) are hot steaming grounds and fumaroles. Surface alteration minerals in the area include kaolin, montmorillonite (smectite) and amorphous silica (Elias, 1984). Since hot springs do not appear at the surface (lower water level), the fumarole gas chemistry is critical for assessing the system.

The gas analysis results and the calculated temperatures from different gas geothermometers are shown in Tables 8 and 9, respectively. H<sub>2</sub>S and H<sub>2</sub> were not detected in the fumaroles except in Koka (located north of the caldera at

a relatively low elevation) which make comparison between geothermometers very difficult. This was because of the high percentage of air contamination.

Koka fumarole is unique among the analyzed fumaroles. Air contamination is very small (1.56 0/0) in Koka. Moreover, the gas concentrations including methane are higher than in other fumaroles in the area.

Even though the variation is small, the estimated temperatures from  $\text{CO}_2$  is higher than those of the other gas geothermometers. All fumaroles indicate a narrow range of temperature when  $\text{CO}_2$  equilibrium temperature function is used (311-333°C).  $\text{H}_2\text{S}-\text{H}_2$  temperatures give similar result 312°C at Koka.  $\text{H}_2\text{S}-\text{H}_2$  temperatures and "corrected"  $\text{CO}_2-\text{N}_2$  temperatures indicate similar results for Koka fumarole (312°C and 286°C). The other geothermometers, i.e. T  $\text{H}_2\text{S}$ , T  $\text{CO}_2-\text{H}_2$  and T  $\text{H}_2$  show lower values. This is presumably mostly due to reactions in the upflow.

All the above results suggest that Koka is the nearest to the source and that the reservoir is situated north of Corbetti Caldera and may have temperatures in excess of 300°C. The low resistivity (10 Ohmm) in this locality which extends north to the southern shore of Lake Shalla provides additional evidence for the existence of high underground temperature (Mohammedberhan, 1984). The gas equilibrium temperatures estimated by Glover (1976) are rather low ( T  $\text{CH}_4$  = 168°C and T  $\text{NH}_3$  = 187°C).

## 6 MIXING PROCESSES

Hot water ascending in geothermal systems may cool by conduction of heat to the surrounding rock, boiling, and mixing with cooler water, or by a combination of these processes.

Geothermometers indicate the temperature at the point of last re-equilibration underground. Hence their application to mixed waters, especially when chemical equilibrium is attained after mixing, will give the temperatures of the mixed water rather than the hot water component. The study of mixing processes in the upflow zones is therefore very important. The application of mixing models, rather than solute geothermometers alone is useful in evaluating the temperature of the hot water component in the mixture.

### 6.1 Evidence for mixing

In most cases geothermal water is higher in dissolved solids than cold water. The mixture lies inbetween the two depending on their proportion in the mixture. Fournier (1979b) and Arnorsson (1985a) discussed the characteristics of mixed waters in detail. Some of these are :

(1) variations in chloride concentration of boiling springs is too great to be explained by steam loss;

(2) variation in concentrations but not in ratios of relatively conservative elements that do not precipitate from solution during movement of water through rock, such as Cl/B;

(3) variation in oxygen and hydrogen isotopes (especially tritium);

(4) cool springs with large mass flow rates and much higher temperatures indicated by chemical geothermometers (greater than 50°C);

(5) systematic variations of spring compositions and measured temperatures;

(6) low pH relative to the water salinity (often in range of 6-7 for Cl concentrations of less than 100 ppm) and high total carbonate, at least if the mixing has prevented boiling, and the temperature of the hot water component exceeds some 200°C;

(7) the tendency of calcite undersaturation; and

(8) low calcium/proton activity ratios.

Mixing in geothermal systems, if it occurs, can be convincingly demonstrated when data on the chemical composition of scattered thermal and cold waters is available. Linear relations between Cl, B, and O-18 constitute the main evidence for mixing. Also similar relations between Cl, SiO<sub>2</sub> and SO<sub>4</sub> concentrations may substantiate evidence for mixing ( Arnorsson, 1985a).

#### Lake Abaya area

D/H versus O-18/O-16 variations in selected thermal and cold waters from the Lakes District geothermal areas are shown in Fig 8. All the Lakes and most shallow wells plot very close or on the line describing D and O-18 for evaporative lakes in East Africa according to Craig (1977).

Abaya spring 6, the hottest and the most mineralized shows considerable oxygen shift. All the other springs plot very close to the precipitation lines. Spring 6 has the highest hot water fraction as indicated from mixing models. Therefore the oxygen shift should be a result of hot water-rock interaction at higher temperatures but steam loss may also contribute.

Fig. 9 shows the relation between Cl, B, O-18, SiO<sub>2</sub> and SO<sub>4</sub> for waters from Lake Abaya. Except for spring 6 all the other springs are very low in chloride making it difficult to conclude with certainty about mixing in the upflow.

### Lake Awasa-Wondo Genet area

Thermal springs in Lake Awasa-Wondo Genet area show little or no oxygen shift except small shift at Wondo Genet spring 41 (Fig. 8).

The geothermal waters in this area are mixed as indicated by near linear to linear relations of Cl-B, Cl-O-18 and Cl-SO<sub>4</sub> (Fig. 10). The Cl-SiO<sub>2</sub> relationship indicates much silica precipitation from sample 40. The sample from spring 40 unlike the others in the area has high concentrations of carbonate, chloride, lithium, sodium, potassium and sulfate.

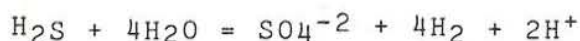
### Lake Shalla area

Spring 30, the most vigorous spring in the Shalla area, shows significant O-18 shift. Craig, 1977 explained this shift as being due to mixing of 50% Lake Shalla water and low chloride groundwater. On the other hand Craig (1977) suggested Shalla 90 (with small oxygen shift but higher in Cl due to contamination) as a more likely source. But spring 90 is steam heated as discussed in section 4. Therefore, the suggestion of spring 90 as a source is unlikely.

Mixing processes are convincingly demonstrated for the Shalla area by the Cl-B relation (Fig. 11). Data on O-18 are limited to only a few springs, No. 30, Shalla cold spring, and springs which are steam heated or contaminated/evaporated.

The eastern Shalla springs show a positive Cl-temperature relation, but the reverse was obtained for Cl-SiO<sub>2</sub>. The analyzed silica in the area is almost equivalent to amorphous silica saturation at the discharge temperature.

Cl-SO<sub>4</sub> in this area shows a negative relation. The redox equilibria involving hydrogen, sulfide and pH might be the controlling factor for sulphate mobility



Similar relation was seen in Landmannalaugar waters, Iceland (Arnorsson, 1985a).

The solute geothermometers indicate temperature of about 200°C. This is expected to be minimum because mixing prevented the solute geothermometers to give higher values underneath Shalla area. This is a supporting evidence for the oxygen shift of the Shalla spring 30 as being a result of hot water/rock interaction and steam loss rather than mixing of low Cl groundwater with water from Lake Shalla. Hence Lake Shalla is a perched water which is not involved in mixing processes. It attained its concentration through extensive evaporation.

#### Lake Langano area

Springs with relatively high amount of cold water fraction in the Langano geothermal area lie on the precipitation line. In case of spring 11 in Geyser Island, there is an oxygen shift, but this is explained by Craig (1977) as steam heated perched groundwater. Mixing in the Langano area is evidenced by a near linear relation of Cl-B and Cl-18-O (Fig.12). The SiO<sub>2</sub>-Cl relation is not good, presumably due to some silica precipitation. The same thing applies to the Cl-SO<sub>4</sub> relationship, most likely due to reactions affecting SO<sub>4</sub> in the upflow.

#### 6.2 Mixing models

As evidence exists that the hot spring waters in all the geothermal areas of Lakes District are of mixed origin, an attempt was made to use mixing models to estimate the temperature of the hot water component. Silica-enthalpy and silica-carbonate mixing models have been applied (Figs. 13 and 14).



### 6.2.1 Silica-enthalpy warm spring mixing model

This method is applicable to warm spring waters that have not lost heat before mixing except by steam formation. It is assumed that no loss of heat, nor steam formation occurs after mixing. The initial silica content of the deep hot water is assumed to be controlled by the solubility of quartz, and no dissolution nor deposition of silica occurs before or after mixing.

The silica-enthalpy warm spring mixing model was applied to Lake Abaya, Lake Awasa-Wondo Genet and Langanu areas assuming no steam loss and was found to give temperatures for the hot water component of 266°C, 213°C and 223°C, respectively. The chloride-enthalpy mixing model gives similar results for the Langanu area, 220°C (Melaku, 1983). These temperatures are lower than both those of gas geothermometry estimates and those encountered in the high temperature drillholes. For example this temperature for the Lake Langanu area is lower than the temperature encountered through drilling by 100°C. This is most likely due to removal of silica from solution in the upflow.

The most vigorous Geyser Island springs which are far from Aluto have the highest hot water component as indicated by their salt content. This must be due to variable mixing in the upflow and that the Geyser Island springs have a better access to deeper, less mixed waters as they are located near vertical fractures.

### 6.2.2 Silica-carbonate mixing model

If there are sufficient data on warm waters containing an unboiled hot water component, the SiO<sub>2</sub>-carbonate diagram may be used to evaluate the temperature of the hot water component (Arnorsson, 1985a). This model assumes that the total carbonate species will appear as CO<sub>2</sub> which is a satisfactory approximation at temperatures higher than 200°C. In addition to the evaluation of the hot water components, this model gives the opportunity to distinguish boiled and unboiled waters.

The temperature of the hot water components as indicated by this model are 297°C and 284°C for Lake Abaya and Lake Awasa-Wondo Genet, respectively (Fig.14). The SiO<sub>2</sub> values of the reservoir fluids underlying Abaya and Wondo Genet areas as inferred from this model correspond to 660 and 610 ppm. The results of this model are in a good agreement with the results of the CO<sub>2</sub> gas geothermometer and, sometimes with that of Na-Li geothermometer and sulfate-water isotopic temperatures.

Assuming the cold water component to have more or less similar Cl and temperature values as the nearby rivers, spring 6 has got the highest hot water fraction (27%) in the area, while all the others are highly diluted. The hot water is estimated to have a chloride concentration of some 2000 to 2600 ppm. The chloride values of the other springs are lower than would be expected from their temperatures. This is best explained by partial steam heating of these waters.

Even though Lake Abaya is enriched in heavy isotopes as a result of evaporation, its salinity is very low (41 ppm Cl). This may open the possibility of Lake Abaya to be involved in the mixing process.

Temperatures estimated by the SiO<sub>2</sub>-carbonate mixing model for Awasa-Wondo Genet area is 284°C. The Na/K temperatures for spring 4, 40 and 52 are 220°C, 214.5°C and 212°C, respectively. The Na-Li geothermometer shows 265°C for spring 4, but higher values for the coldest spring, 44 (which has the characteristics of highly mixed water), and to spring 40 (highest Li in the District which might not be in line with the waters used for calibration). Spring 40 lies below the mixing line of the silica-carbonate model, that is the SiO<sub>2</sub> value is low for the carbonate. A possible cause for this is the precipitation of SiO<sub>2</sub> in the upflow subsequent to mixing. Sulfate-water temperatures for Wondo Genet (Belle Tebel) springs as reported by Craig (1977) are 255°C assuming cooling with steam loss and 318°C assuming conductive cooling. All this suggests the existence of an independent heat source underneath Wondo Genet with a temperature of 250-300°C.

The correlation of silica and carbonate for waters in the Langano area for which data are available is poor (not shown). Possibly the removal of silica is the main cause.

Since the  $\text{SiO}_2$  values of Shalla springs are unreliable (show negative correlation with Cl), use of silica-enthalpy and silica-carbonate mixing models are not possible. There are no boiling springs except spring 30. The Cl concentrations in the springs are variable. Thus, an attempt has not been made to use the Cl-enthalpy mixing model. However, Na/Li and Na/K geothermometers, indicate an independent heat source underneath Shalla with temperature in excess of  $200^\circ\text{C}$  (see Table 6). It seems unlikely that the Shalla springs are an outflow from Aluto-Langano and Corbetti geothermal areas which are 40 and 25 km away respectively. This is convincing especially when the results of shallow and/or deep wells between Shalla and the respective fields are considered. The close resemblance between Chittu and South Shalla springs clearly demonstrates that the former springs are an outflow from Shalla. Reliable  $\text{SiO}_2$  determination of Shalla springs and complete chemical data from shallow wells inbetween Shalla and Corbetti will assist in confirming this result.

## 7 SUMMARY

1. The waters in the Lakes District have near neutral pH and are primarily of the sodium bicarbonate type. Mixing with cold waters occurs invariably in the upflow. The hot water components underlying the geothermal areas in this district contain dissolved total carbonate in the range of 3000-5000 ppm.

2. The gas geothermometers of Arnorsson and Gunnlaugsson (1985) give probably good picture of subsurface temperatures for Lakes District geothermal systems. Condensation is always strong in the upflow. Hence CO<sub>2</sub> temperatures tend to give high estimates of subsurface temperatures. Sometimes the sulfate-water isotope geothermometer and Na-Li results are similar to the CO<sub>2</sub> temperature. Because of mixing, the solute geothermometers yield low results when surface geothermal fluids are used to estimate the subsurface temperature.

3. The silica-carbonate mixing model seems to give the most reliable results of all the mixing models in the estimation of the reservoir temperatures in Lakes District, where there are few boiling springs in each locality and the temperature distribution is highly affected by mixing.

4. A hot water body exists underneath Aluto-Langano Complex with temperature in between 320°C and 340°C. It flows towards south, southwest, north and east supplying the surrounding springs at lower elevation and fumaroles at higher elevations.

5. Shalla probably has its own heat source with a minimum temperature of 200°C and subsurface flow towards east, south and south west supplying Shalla and Chitu springs.

6. There probably exists a hot water body with temperature in excess of 300°C north of Corbetti Caldera. Flow from the reservoir is probably towards south, southwest and southeast discharging steam at the surface (fumaroles, hot and steaming grounds) in and around the caldera.

7. The springs at Wondo Genet and east of Awasa are possibly fed by a high temperature water of some 250-300°C underneath Wondo Genet.

8. The deep hot water underlying the Abaya area is thought to have silica of about 660 ppm and 2000-2600 ppm chloride with temperatures in the range of 300-350°C. The hot water probably flows to the north, northwest and northeast and mixes with low chloride groundwater.

9. The waters in Lakes District are supersaturated with respect to calcite, nearly saturated with fluorite and highly undersaturated with respect to anhydrite at depth. The waters are somewhat supersaturated with quartz and chalcedony at the surface.

## 8 RECOMMENDATIONS

1. Special attention should be paid to establishing a data base of reliable chemical analyses of the geothermal and surface waters in the Lakes District. Complete chemical analyses of waters in Shalla and Wondo Genet areas are essential to substantiate or disprove the present interpretation.

2. Both hot springs and fumaroles occur in the geothermal fields of the Lakes District except in the Corbetti geothermal area where there are only fumaroles. It is advantageous to use both fumarolic steam chemistry and hot springs chemistry to predict subsurface temperatures.

3. Fumaroles and shallow wells which are located around Corbetti and inbetween Shalla and Corbetti should be sampled and analyzed to understand the Corbetti and Shalla geothermal systems and to see their interrelationship. It would be advantageous to drill more shallow wells in the same area, and in and around the Corbetti caldera to assist the gas chemistry interpretation.

4. Both geochemical and geophysical results indicate the heat source for the Abaya area to be close to the lake. Therefore, chemical sampling and temperature measurement at the bottom of the lake are important to identify any water flow underneath the lake itself.

5. Special approaches are required for sampling and analyzing geothermal fluids. Therefore, it is advantageous for the Geothermal Division to have its own geochemical laboratory.

6. The following equipment are recommended for the geothermal geochemical laboratory for improving precision and the speed of analysis.

(a) Atomic Absorption spectrophotometer

(b) Automatic dilutor: This instrument increases sample preparation for atomic absorption analysis 3-5 times compared to conventional dilution methods.

(c) Coulombimetric chloride titrator. This instrument will improve both the speed and the precision of the analysis as compared with the Mohr titration.

(d) Glass gas sampling bulbs with septum and pressure check valves.

(e) Automatic pipettes with tip ejectors, and fixed volume micropipette.

(f) Silicone tubing suitable for high temperature fluid sampling as they have good heat and solvent resistances.

(g) Digital balance. This is specially useful for gas analysis in terms of accuracy and speed.

(h) An effective cooling system for collection of samples from wells. A system using a motor vehicle radiator has been fabricated in Iceland.

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85.09.1171 AA

JHD-HSP-9000 BG  
85.09.1172 AA

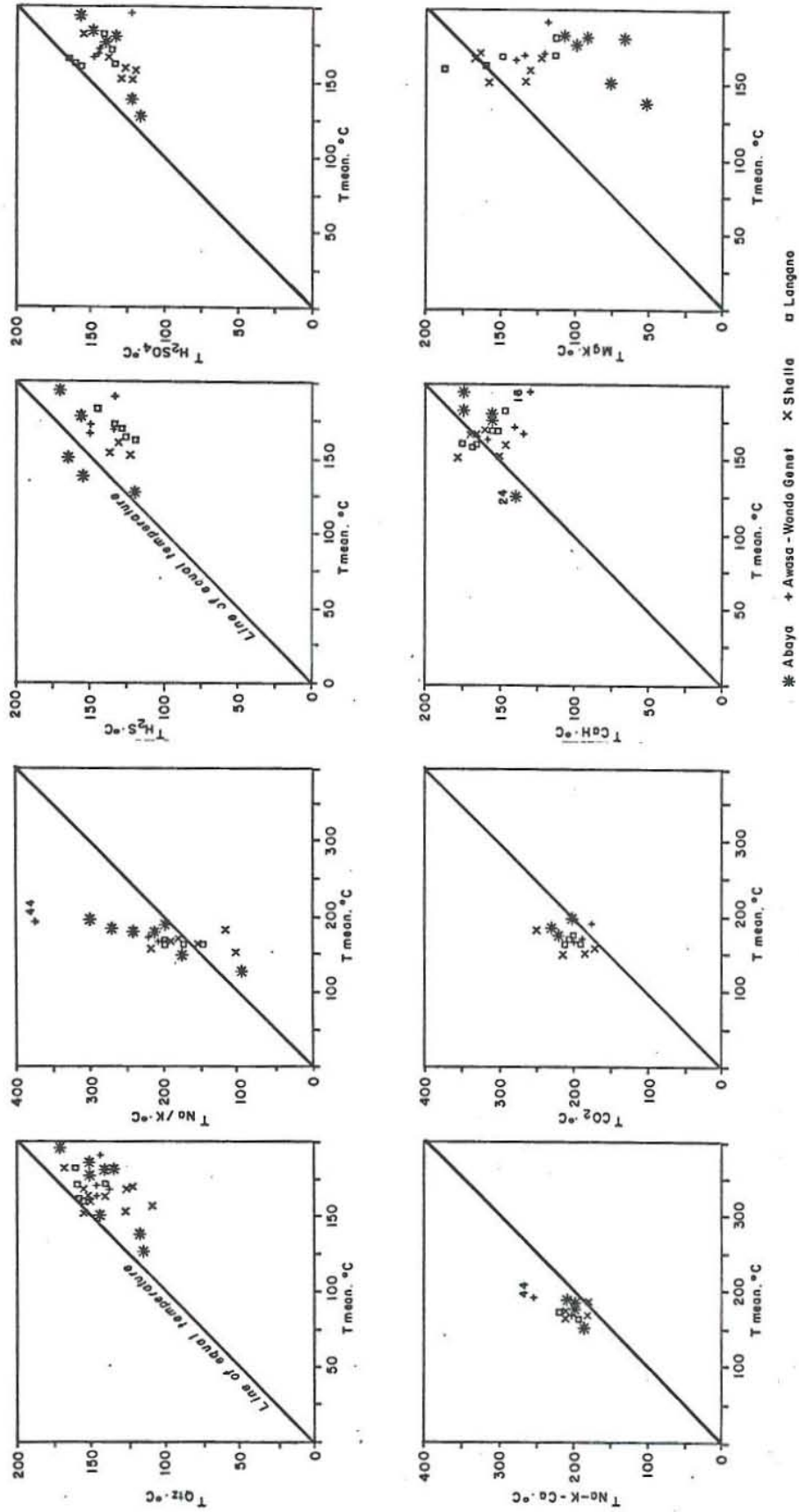


Fig. 2. Comparison between the results of individual solute geothermometers and the mean temperature of all of them.

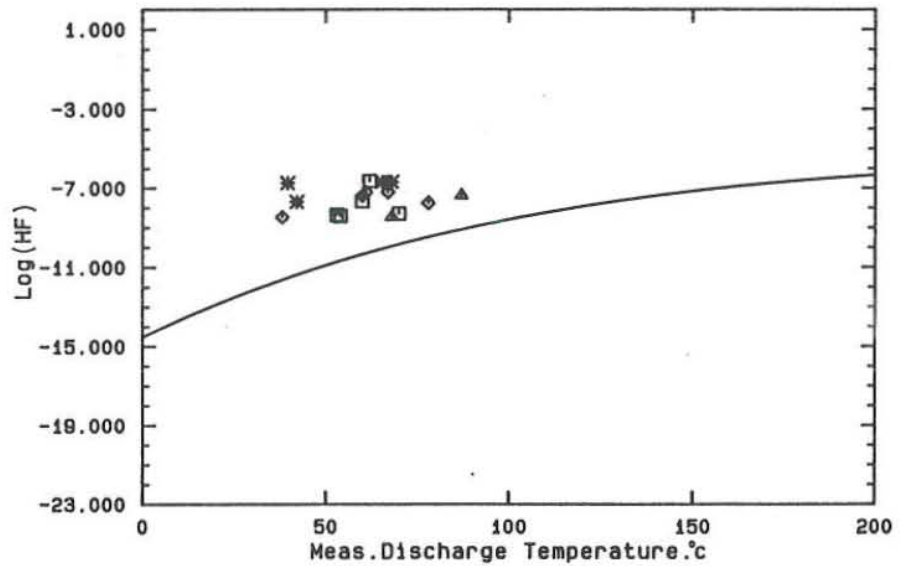
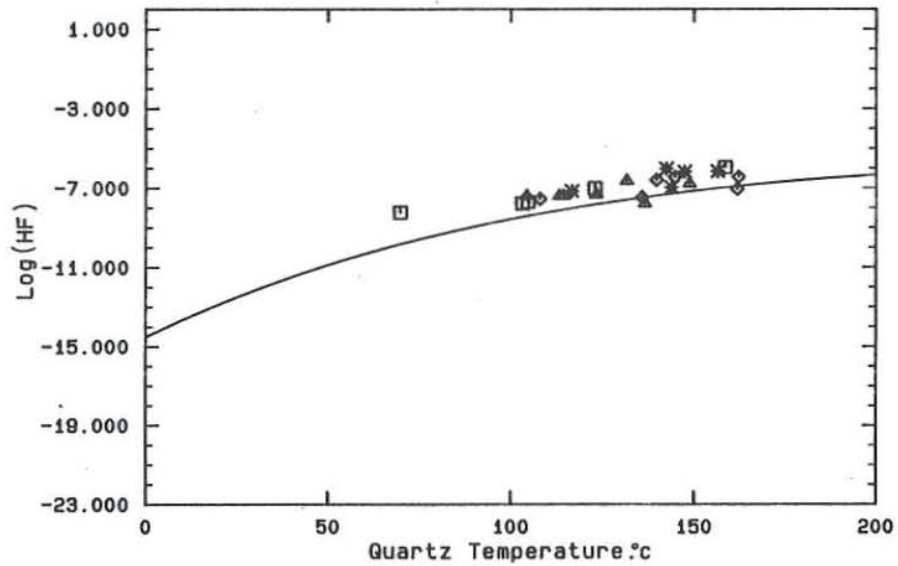
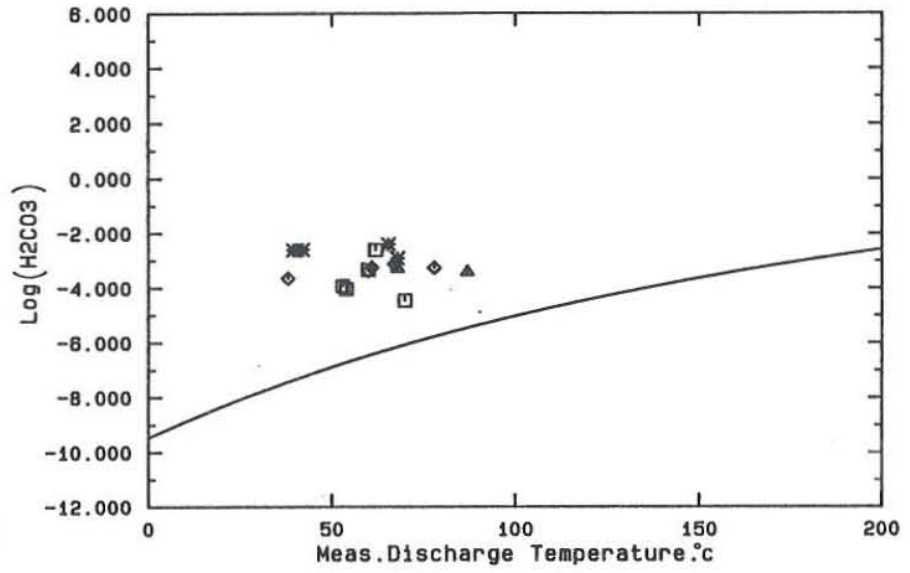
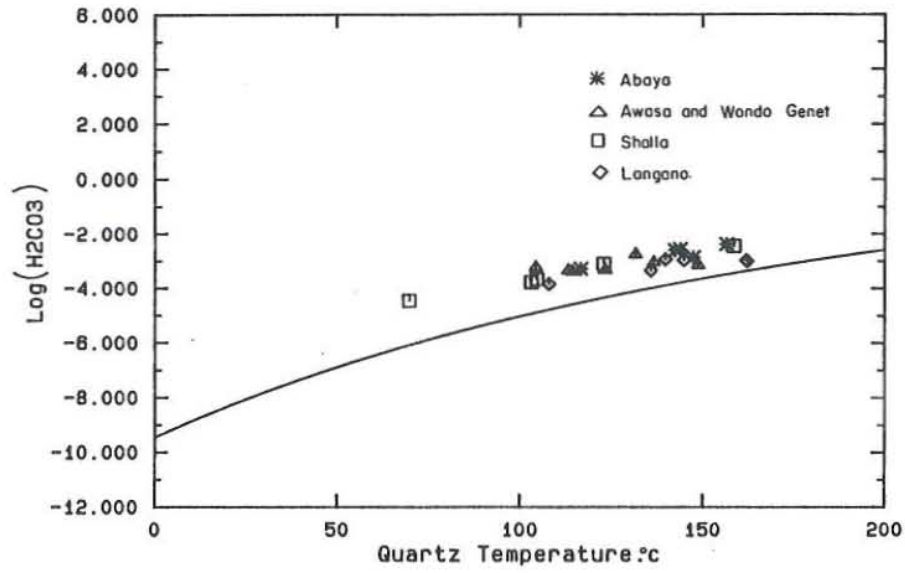


Fig. 3. Relation between carbon dioxide and fluoride concentrations and quartz equilibrium temperature/discharge temperature in the Lakes District geothermal waters.

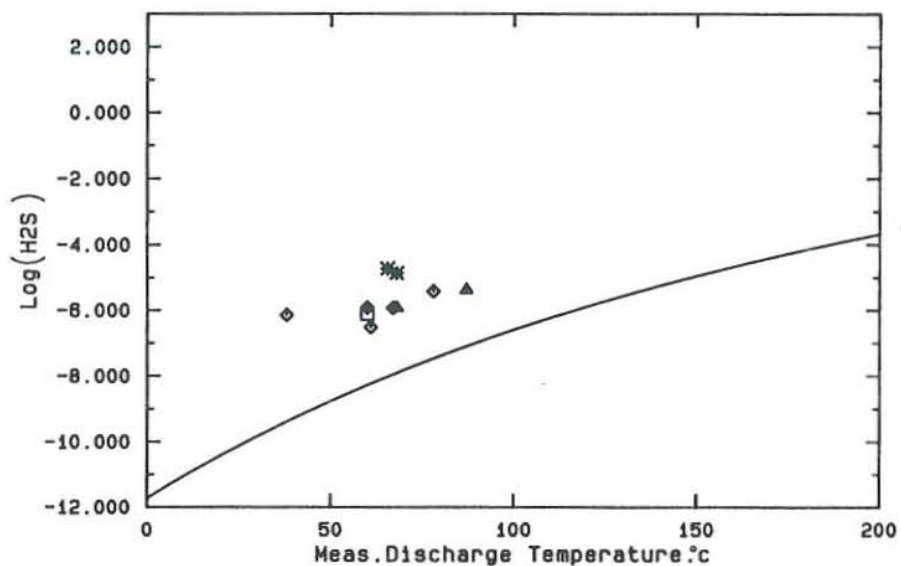
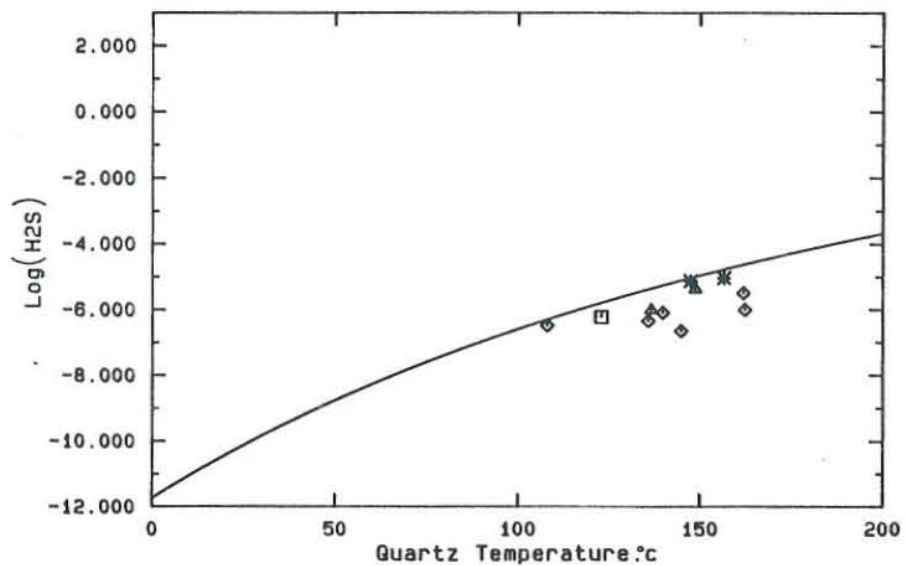
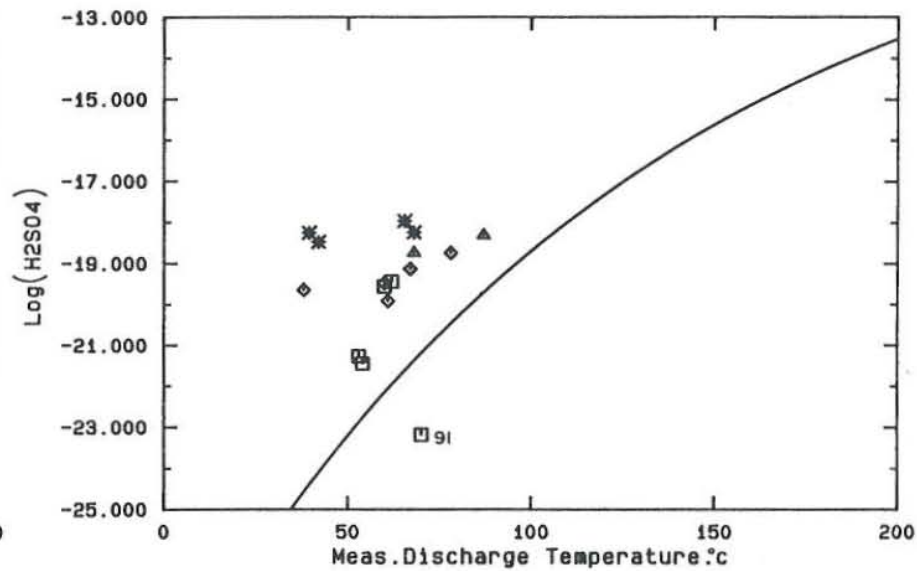
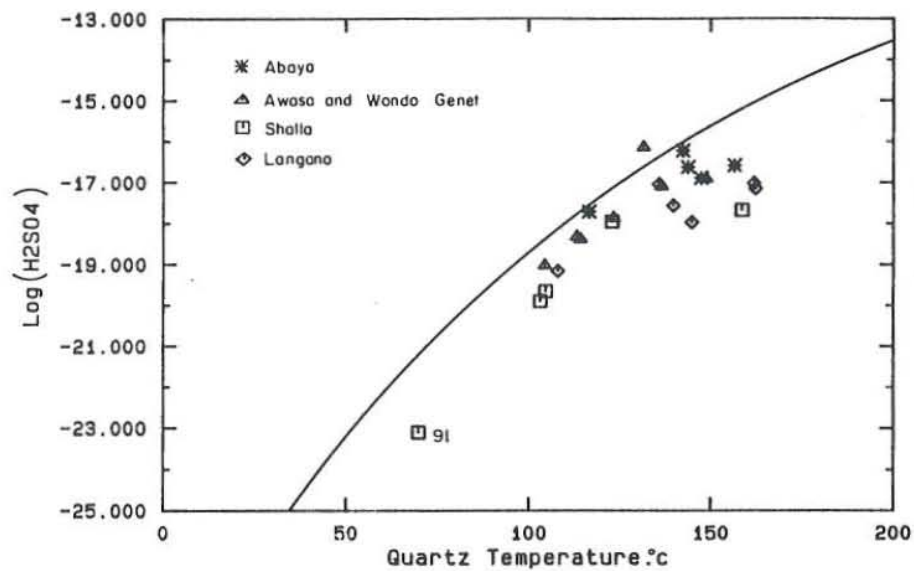


Fig. 4. Relation between sulfate and sulfide concentrations with quartz equilibrium temperature/discharge temperature in the Lakes District geothermal waters.



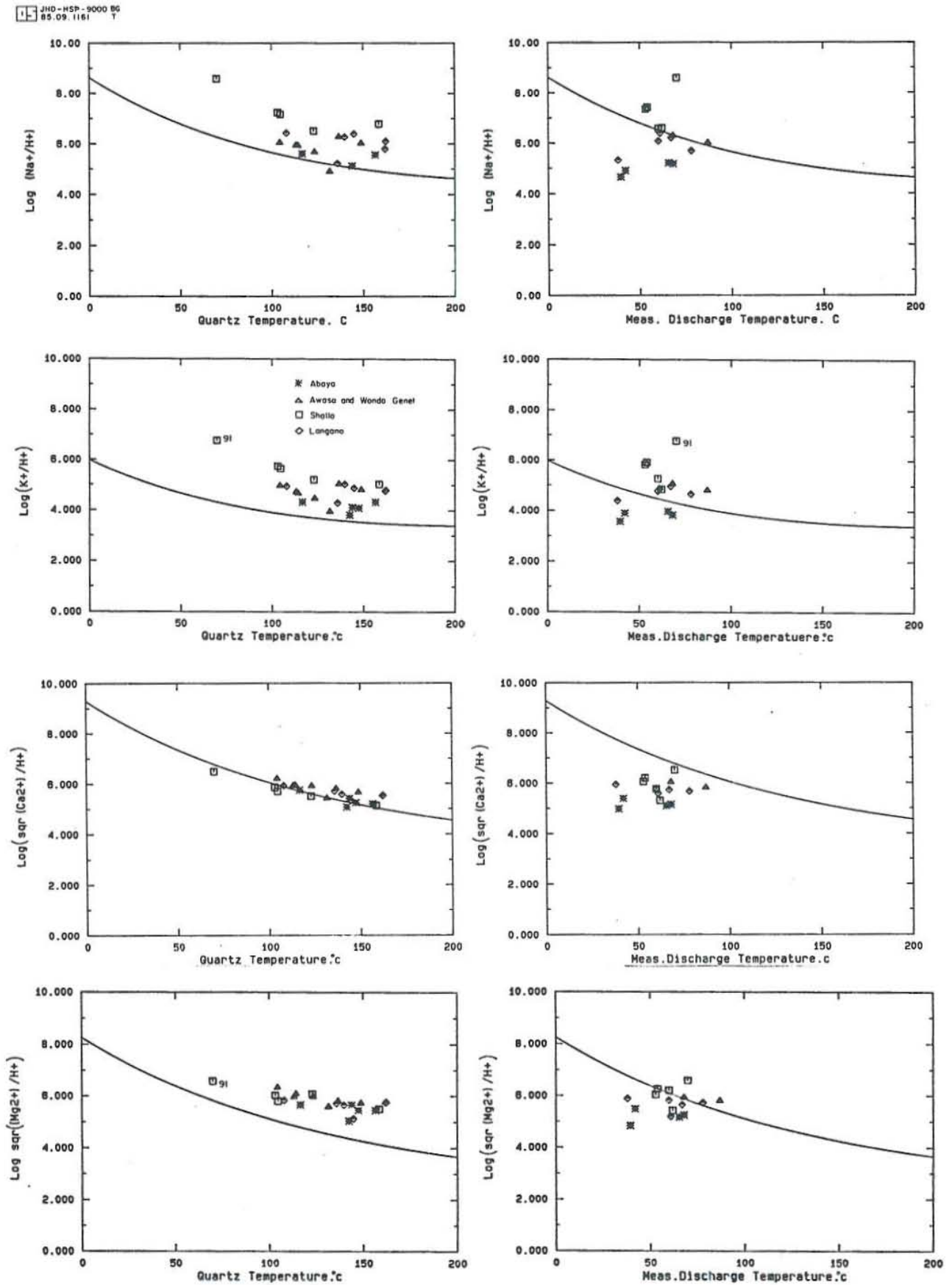


Fig. 5. Relation between cation/proton ratios and quartz/- discharge temperature in the Lakes District geothermal waters.

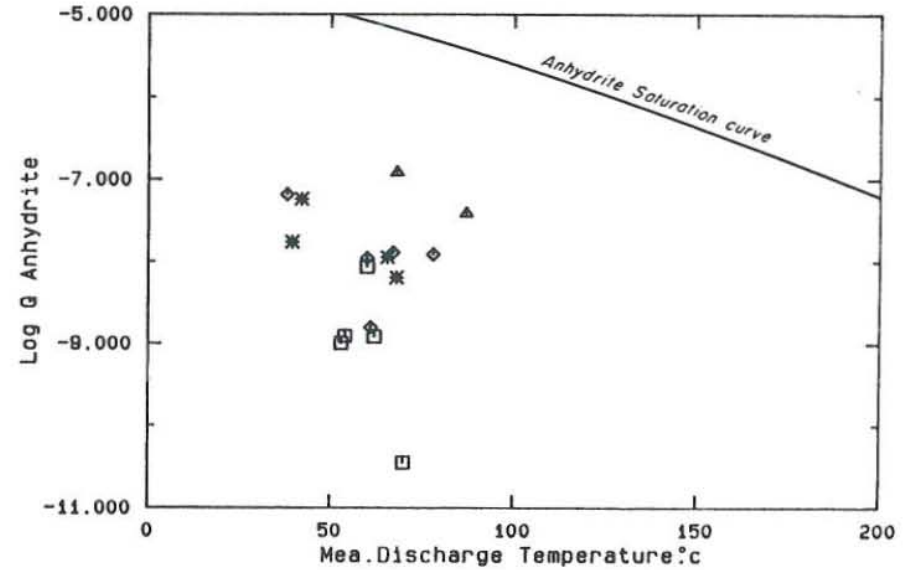
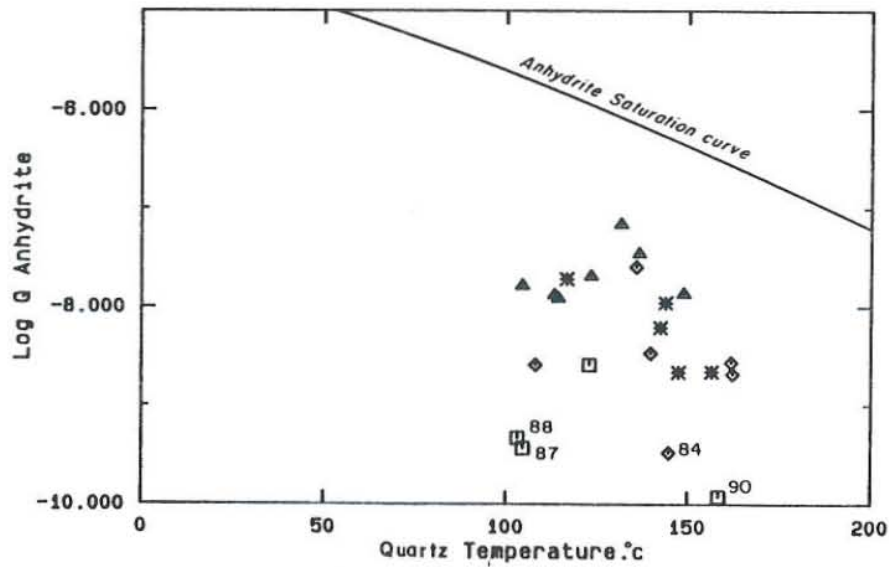
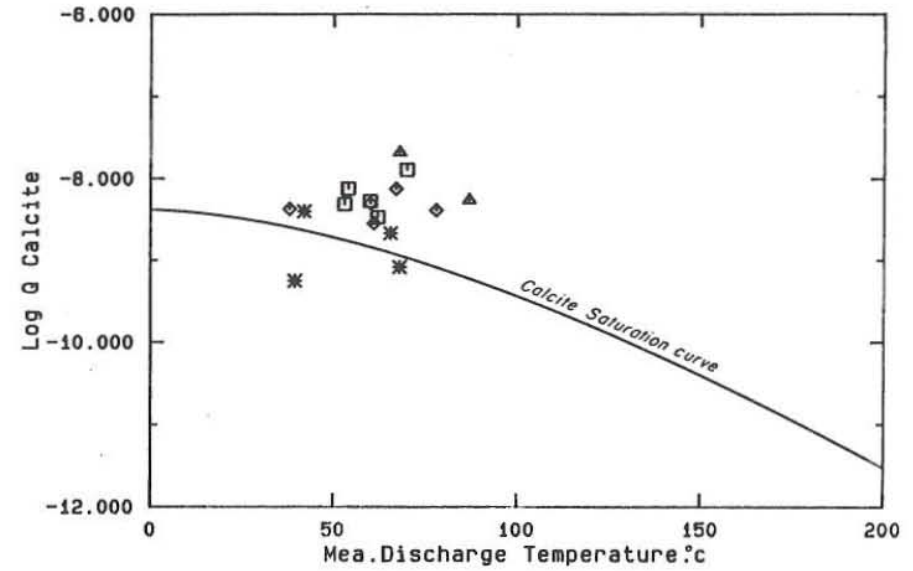
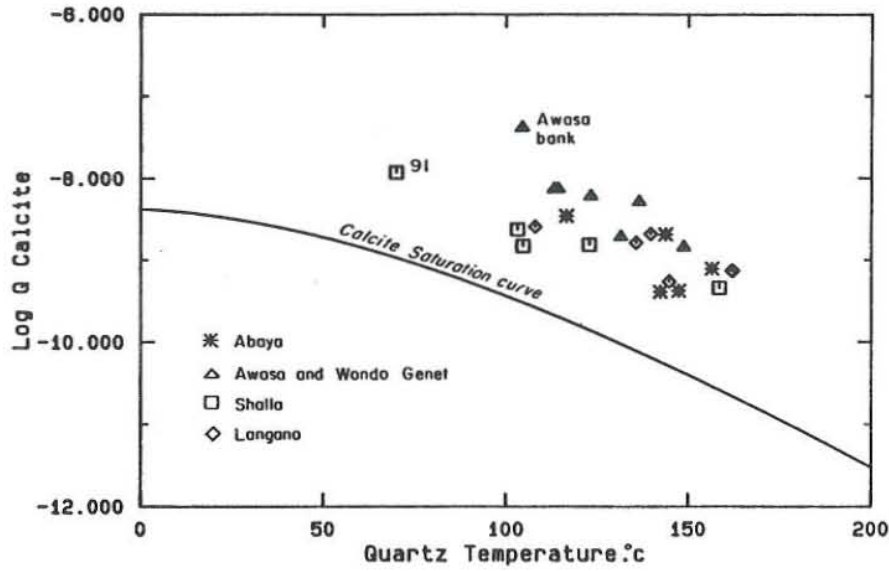


Fig. 6. State of calcite and anhydrite saturation at quartz/discharge temperatures in the Lakes District geothermal waters.

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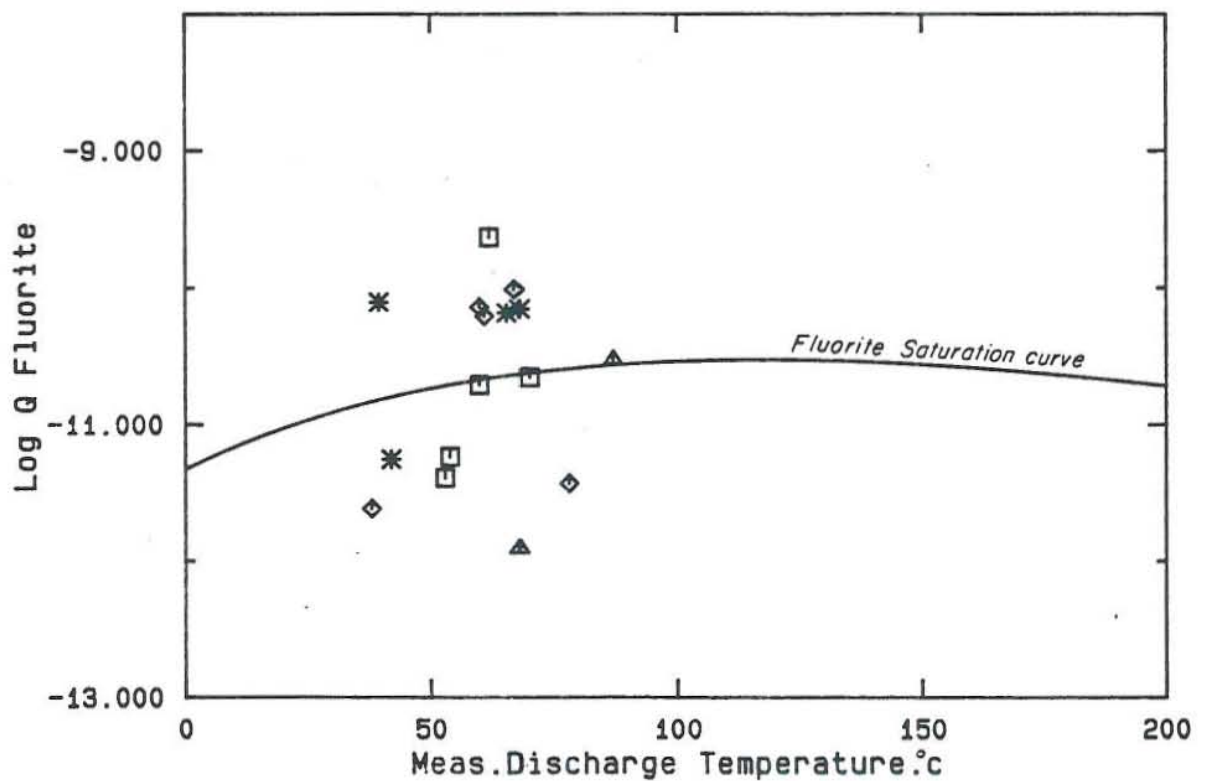
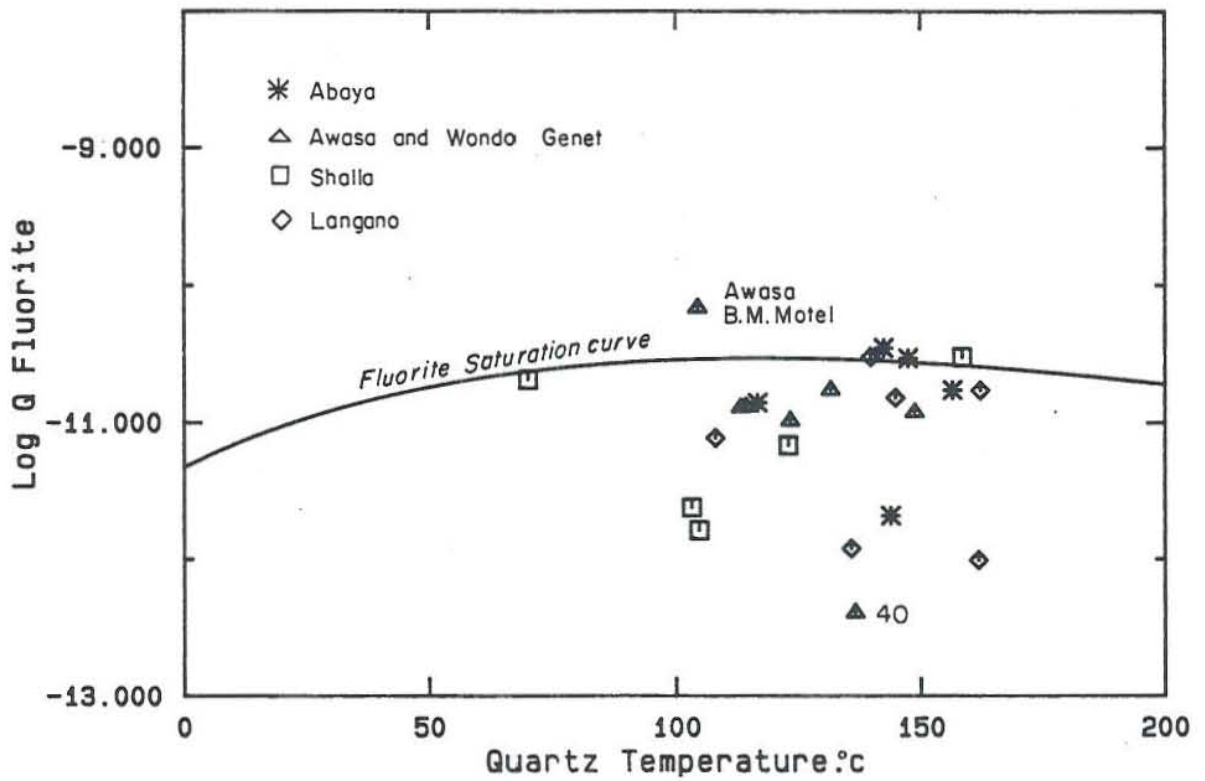


Fig. 7. State of fluorite saturation at quartz/discharge temperatures in the Lakes District geothermal waters.

JHD-HSP-9000 BG  
85.09.1173 AA

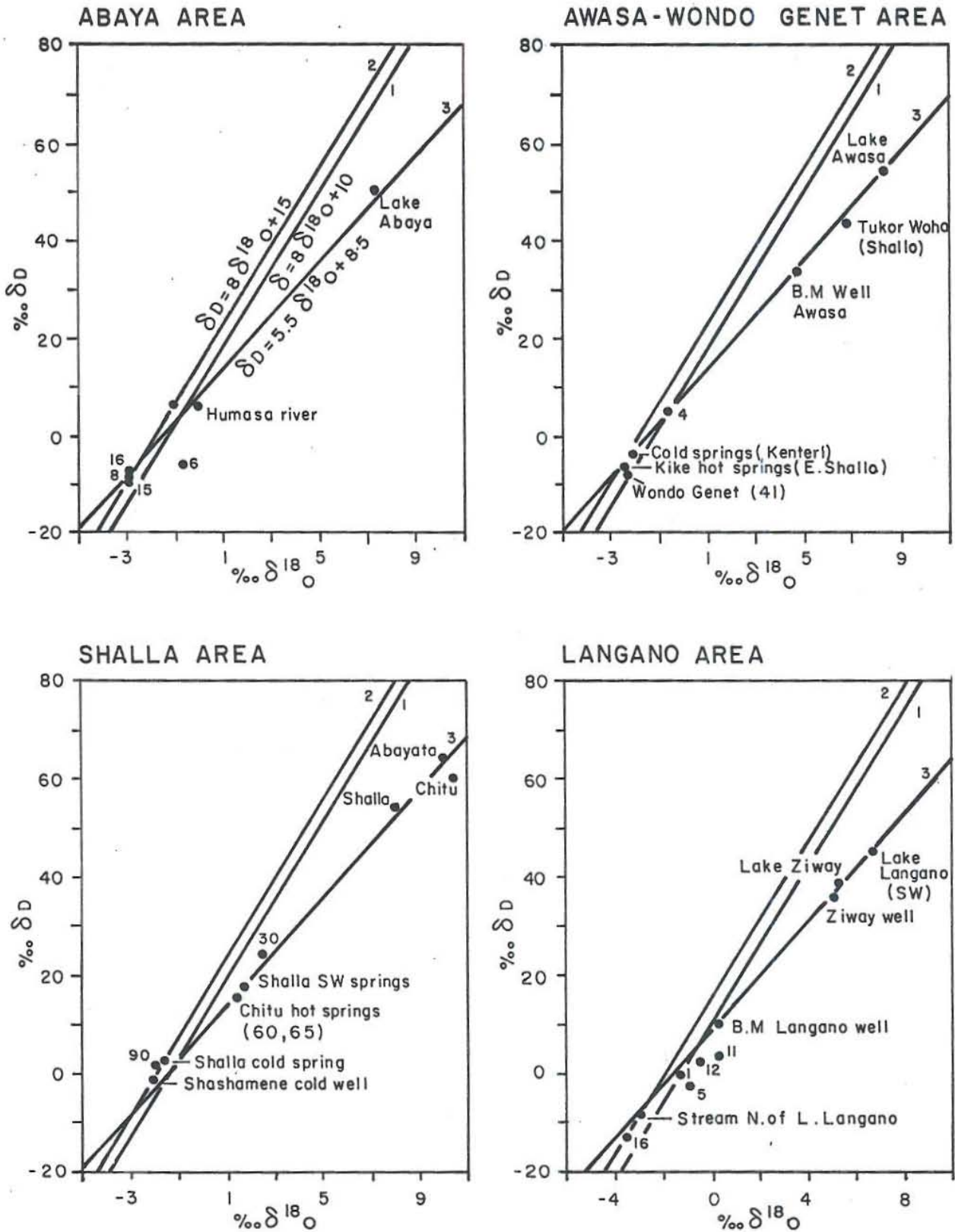


Fig. 8. D/H and O-18/O-16 variations in thermal and cold waters from the Lakes District.

JHD-HSP-9000 BG  
85.09.1170 AA

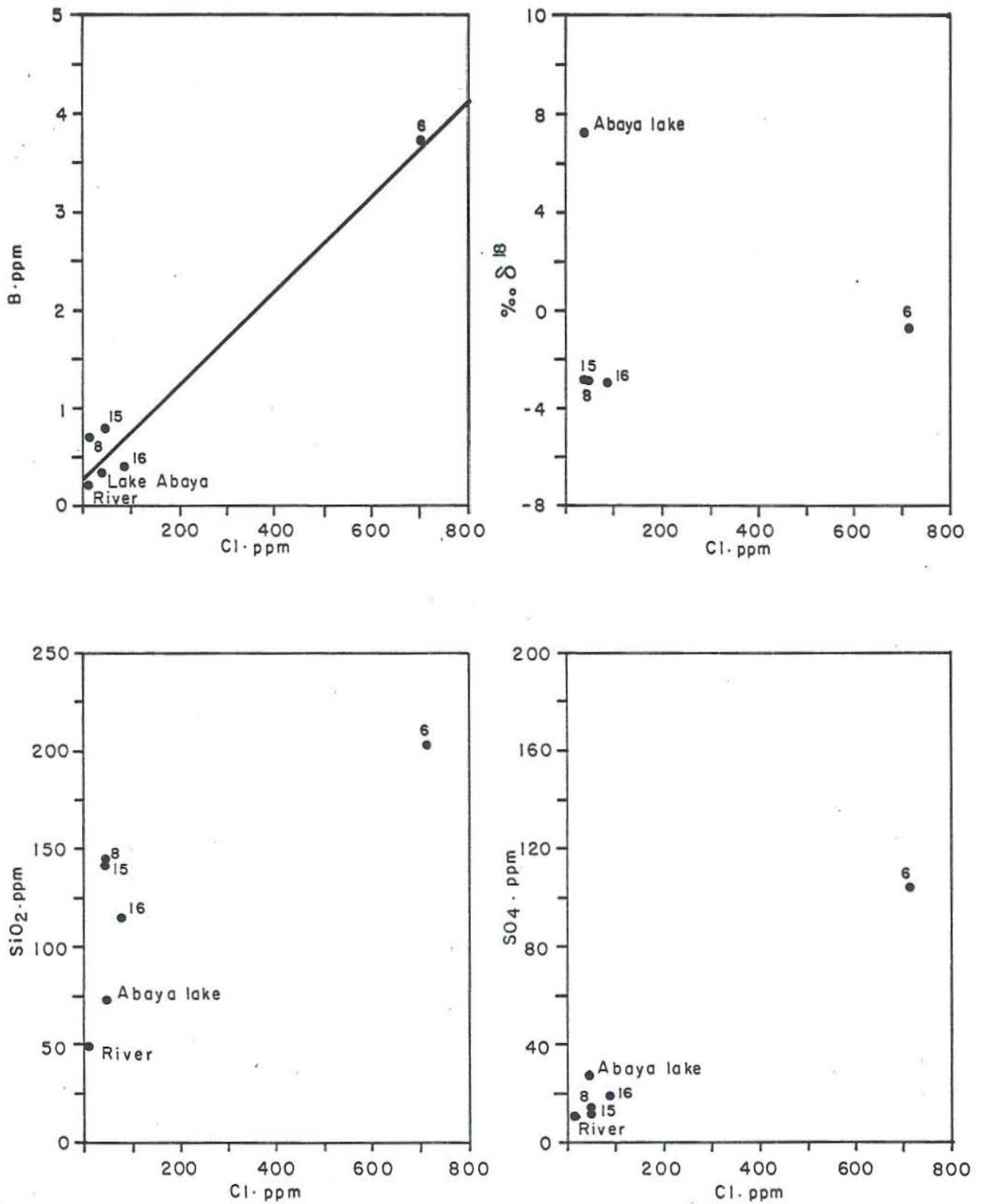


Fig. 9. Relationship between chloride concentrations, boron, O-18,  $\text{SiO}_2$  and  $\text{SO}_4$  in cold and thermal waters from the Abaya area.

JHD-HSP-9000 BG  
85.09.1174 AA

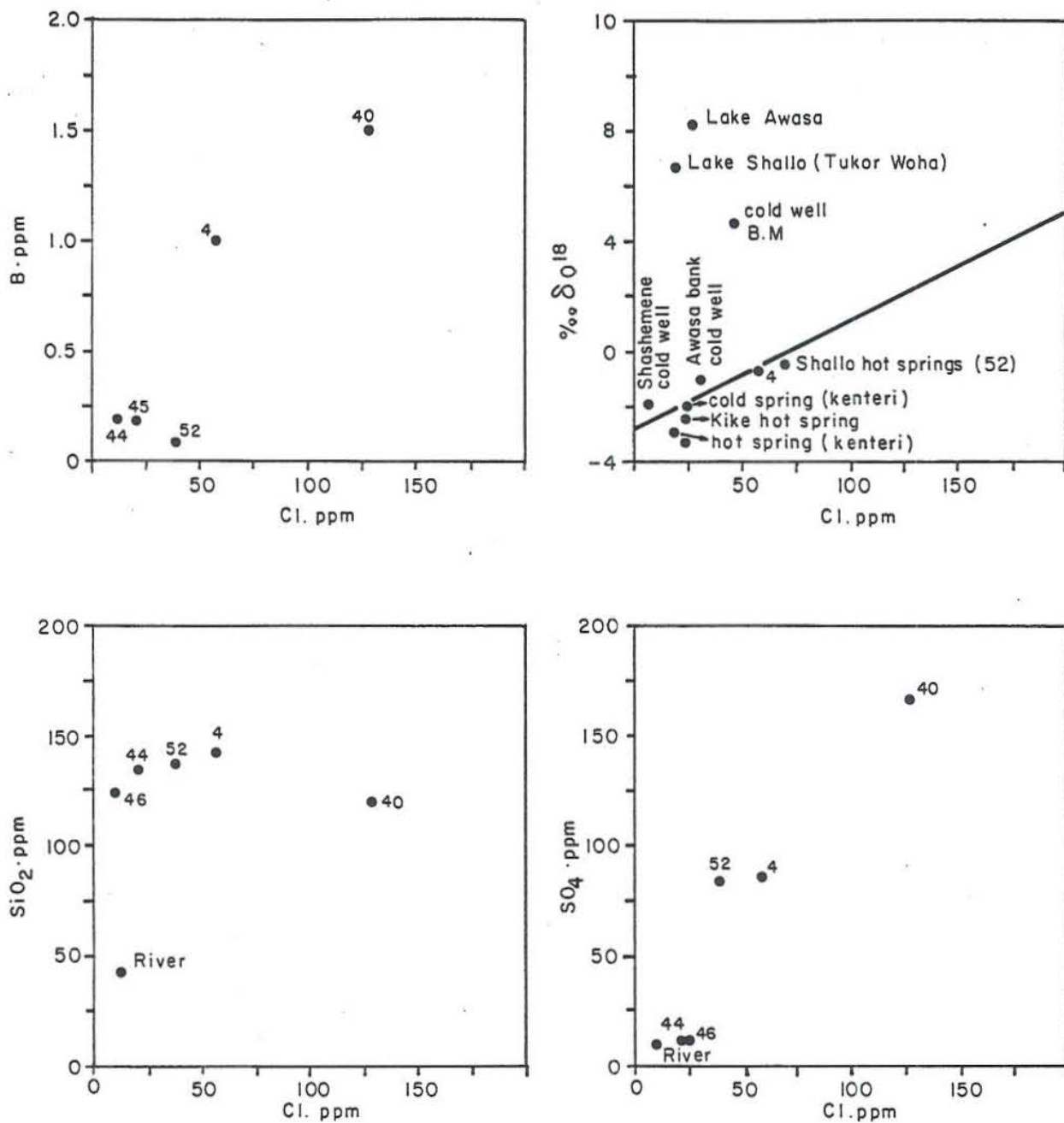


Fig. 10. Relationship between chloride concentrations, boron, O-18, SiO<sub>2</sub> and SO<sub>4</sub> in cold and thermal waters from the Awasa-Wondo Genet area.

JHD-HSP - 9000 BG  
85.09.1169 AA

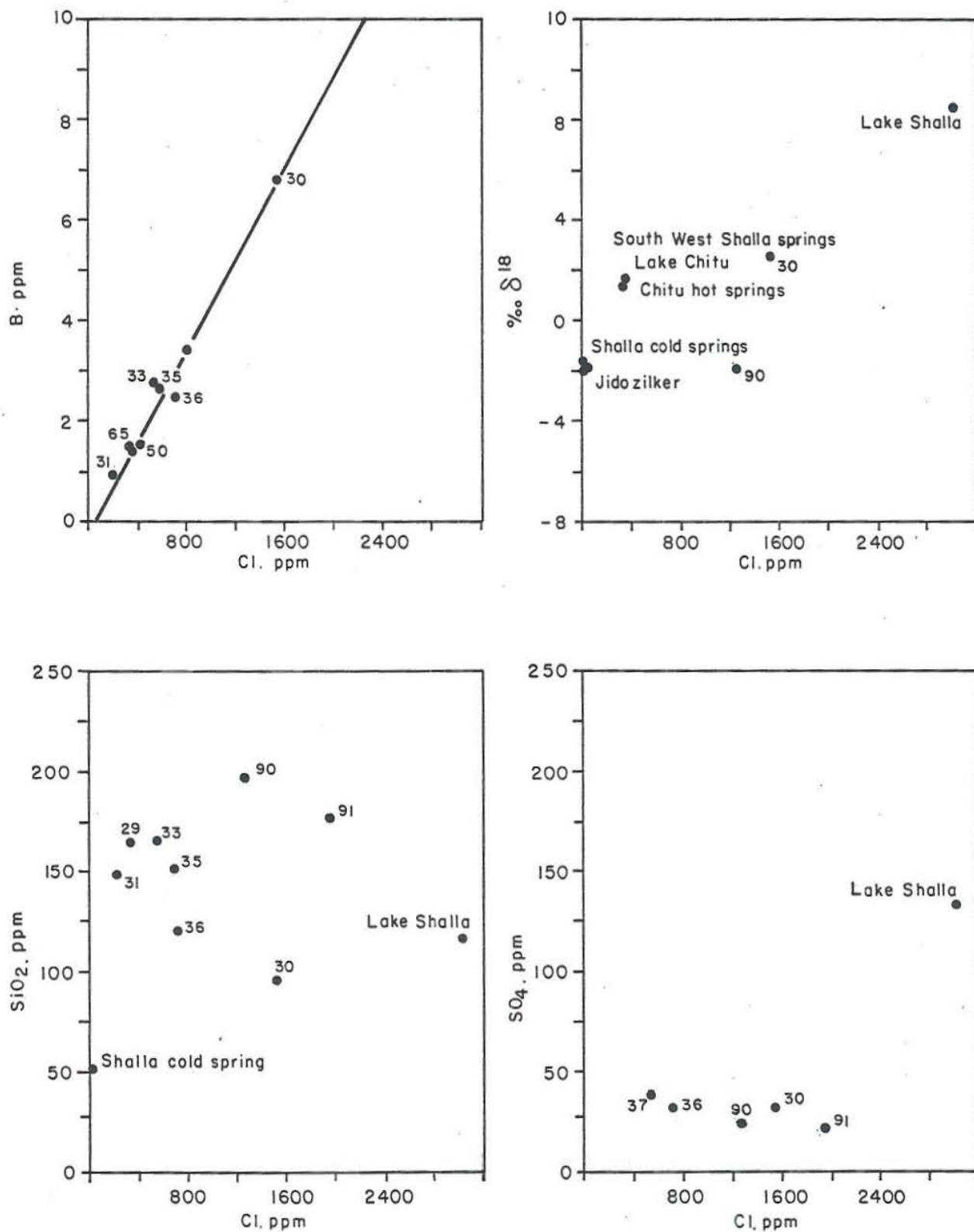


Fig. 11. Relationship between chloride concentrations, boron,  $O-18$ ,  $SiO_2$  and  $SO_4$  in cold and thermal waters from the Shalla area.

JHD-HSP-9000 BG  
85.09.1168 AA

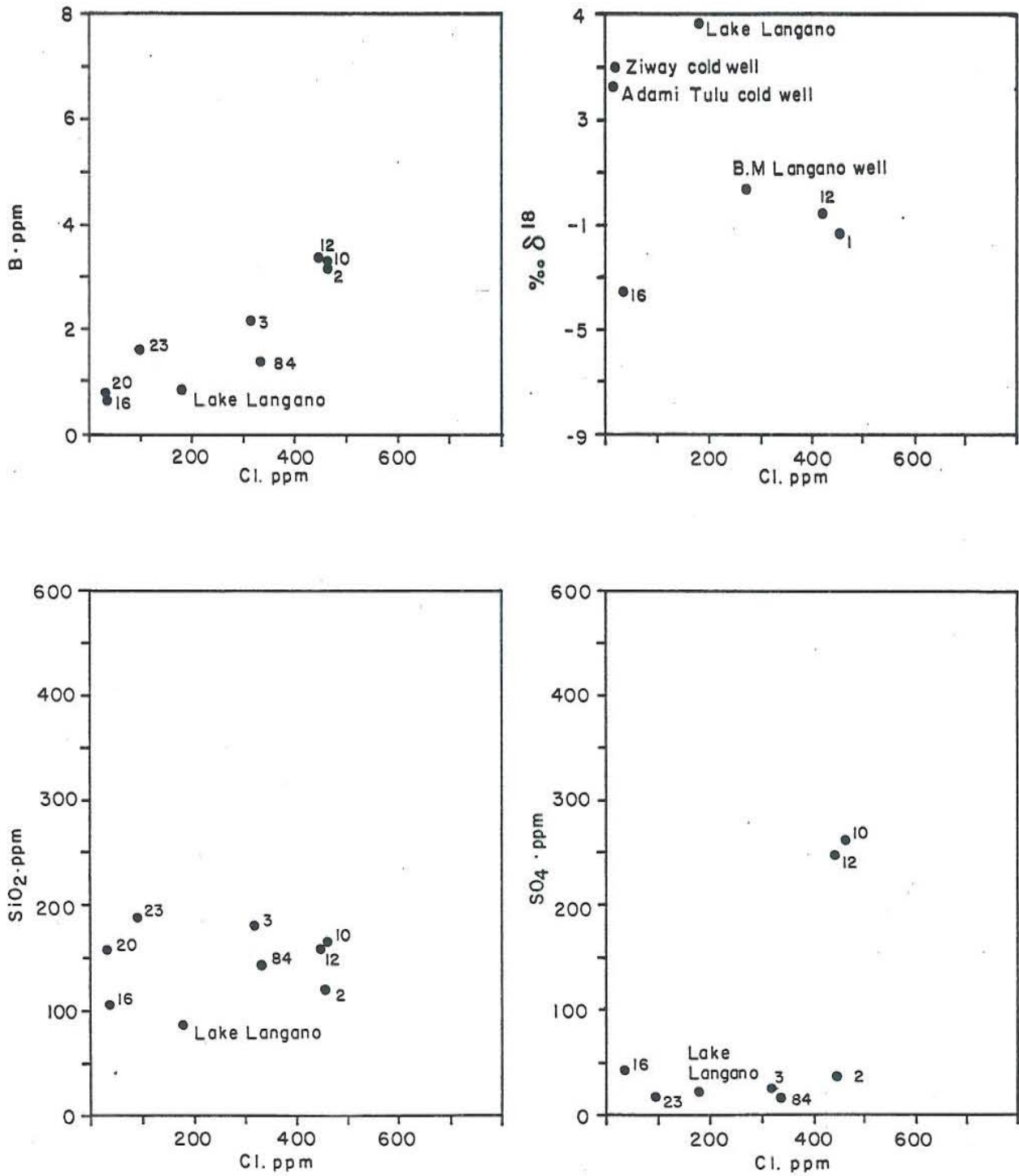


Fig. 12. Relationship between chloride concentrations, boron, O-18, SiO<sub>2</sub> and SO<sub>4</sub> in cold and thermal waters from the Langano area.



JHD-HSP-9000 BG  
85.09.1167 AA

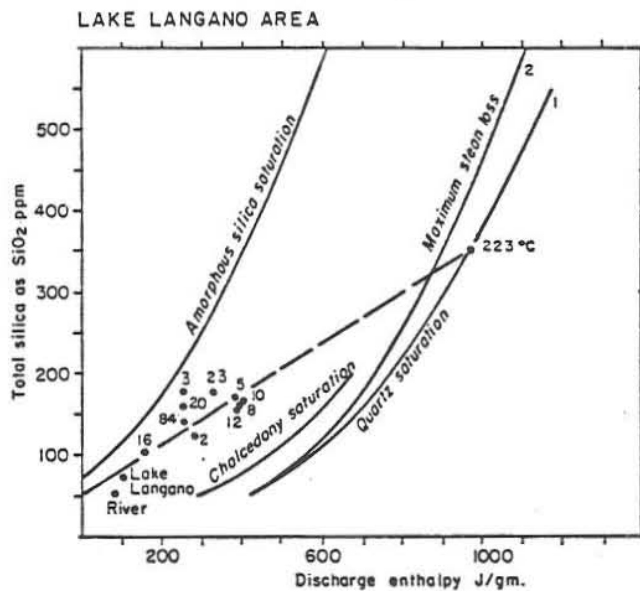
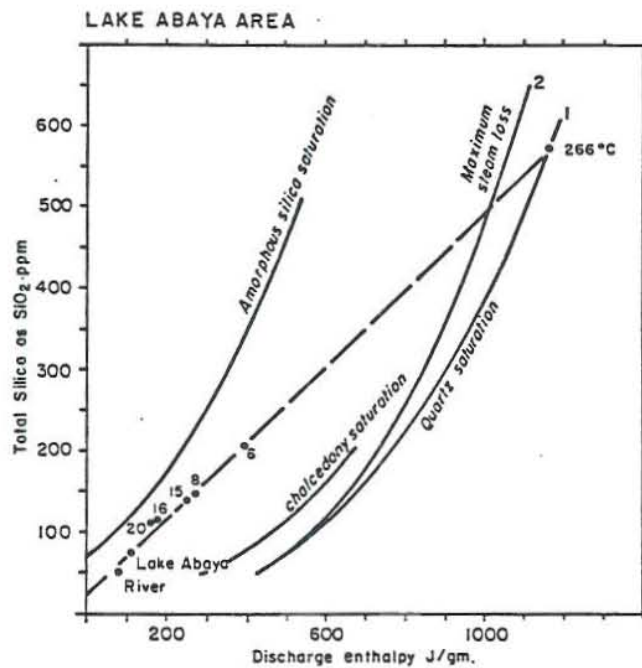
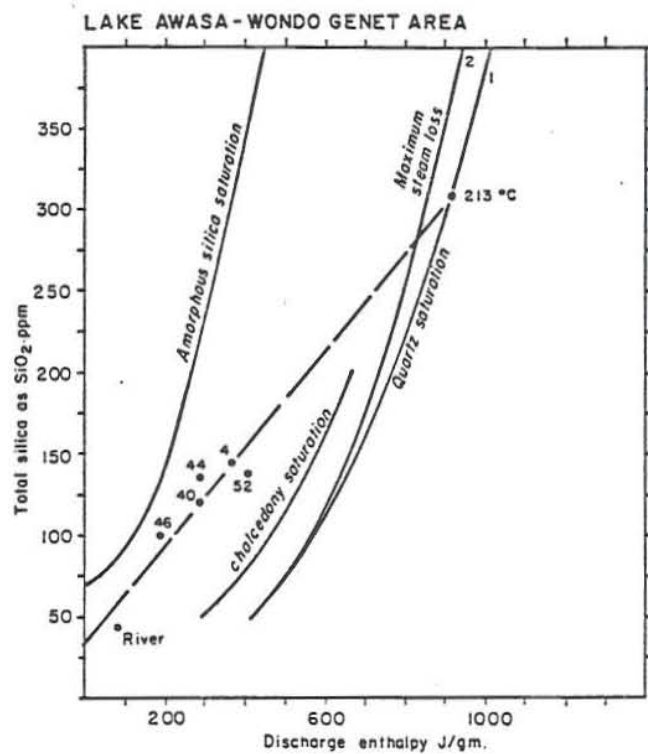
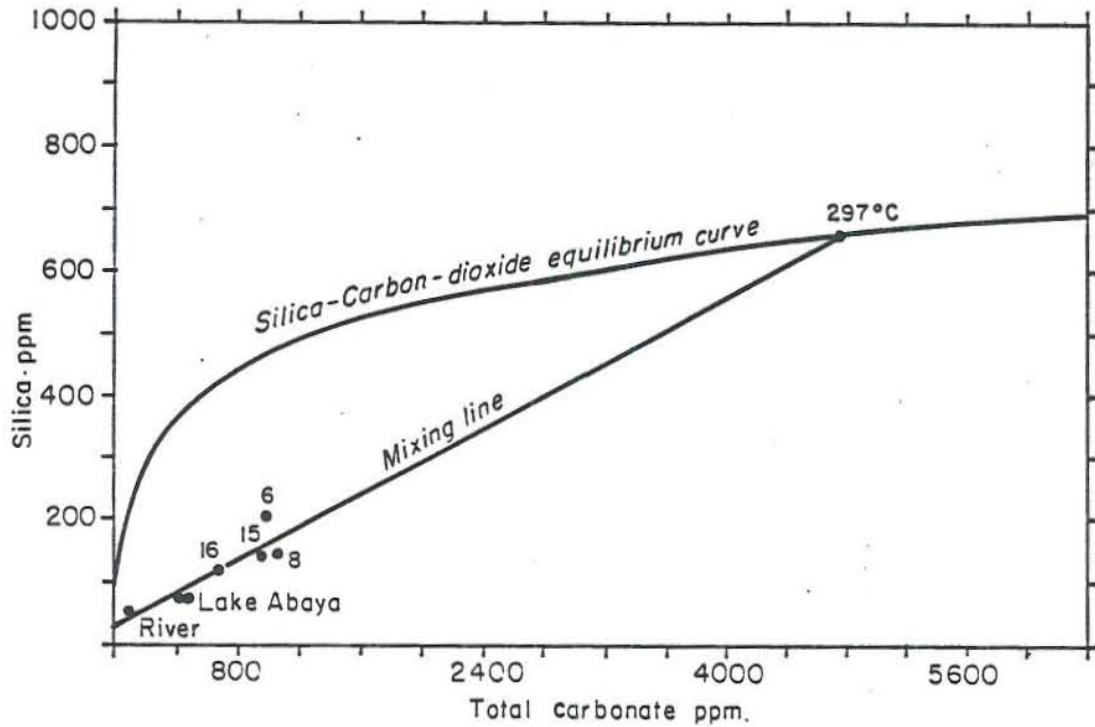


Fig. 13

Silica-enthalpy mixing model. Quartz saturation curves (1 and 2) are based on Fournier and Potter (1982a). Chalcedony and amorphous silica saturation curves are based on Fournier (1981). The broken line represents the silica-enthalpy relationship of the geothermal waters.

JHD-HSP-9000 BG  
85.09.1166 AA

### LAKE ABAYA AREA



### LAKE AWASA-WONDO GENET AREA

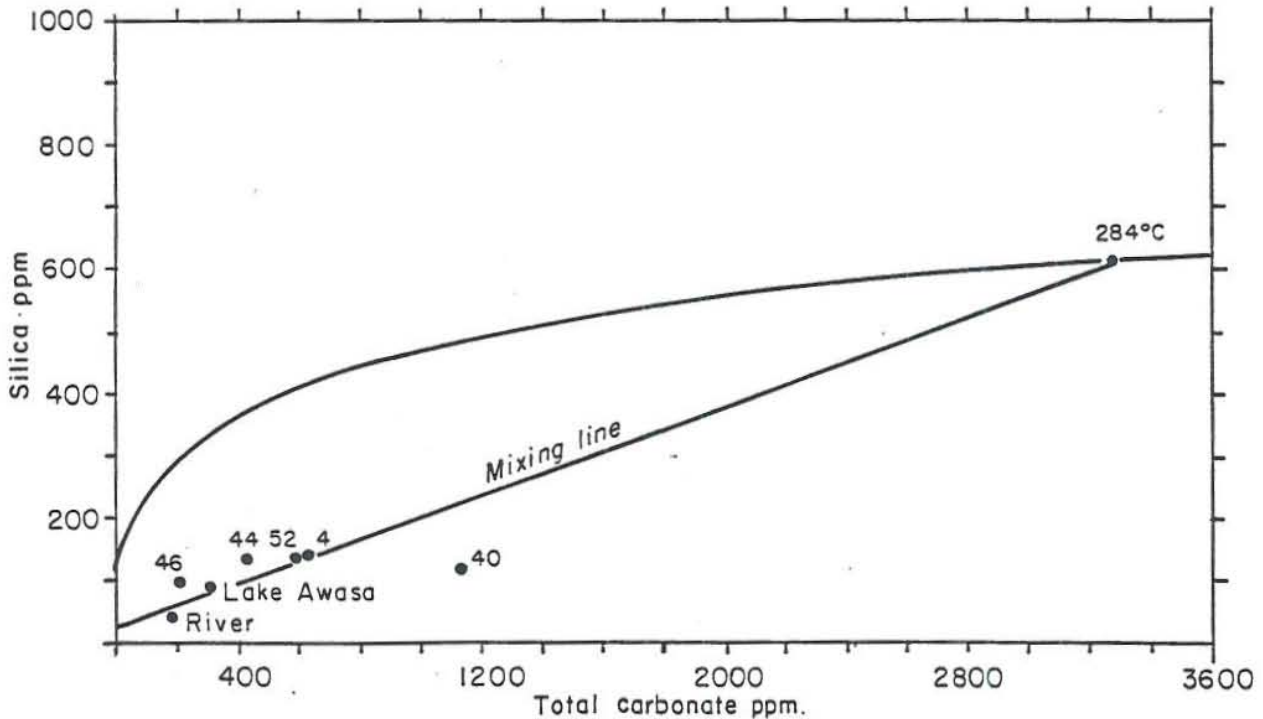


Fig. 14. Silica-carbonate mixing model. The temperature dependence of silica was assumed to be controlled by quartz solubility according to the data of Fournier and Potter (1982).

TABLE 1 Chemical composition of waters in the Abaya Area (ppm)

Location	T (°C)	Flow (l/s)	pH	H <sub>2</sub> S	Total Carbonate (CO <sub>2</sub> )	NH <sub>4</sub>	Li	K	Na	Ca	Mg	F	Br	I	Cl	SO <sub>4</sub>	B	SiO <sub>2</sub>
NB 371616	95	11.6	9.6	7	995.33	1.00	1.80	240	1290	<3	<2	43	na	0.05	711	104	3.73	204
8	65.5	11.5	7.2	2	1059.72	0.19	0.58	50	500	20	14	13	na	0.01	48	12	0.70	146
15	60	20.0	na	nd	950.70	0.32	0.62	50	530	18	9	14	na	0.01	48	12	0.73	141
16	42	9.0	7.2	nd	671.53	na	0.65	39	230	52	48	2	nd	0.02	81	18	0.40	116
19	68	1.6	7.4	2	456.47	na	0.07	22	280	8	7	18	nd	0.01	45	11	0.27	126
20	39.5	83.3	7.0	nd	437.18	na	<0.05	27	194	16	5	12	0.4	0.01	18	11	0.12	112
Lake Abaya	-	-	8.0	na	441.99	na	0.05	20	226	18	5	7	0.7	na	41	27	0.31	73
River Abaya turnoff	-	-	8.3	na	63	na	<0.05	8	17	8	2	0.5	0.2	na	<10	<10	0.18	49

TABLE 2 Chemical composition of waters in Lake Awasa-Wondo Genet Area (ppm)

NB 371614	87	1.0	8.4	3	627	na	0.42	43	397	11	5	13	1.1	0.01	57	86	1.0	143
NB 3712140	68	2.1	8.4	0.9	1134	na	2.20	67	655	23	7	2	0.6	0.02	128	166	1.5	119
52	96	small	8.5	3	594.60	na	0.88	44	430	<3	<2	40	nd	0.01	38	83	0.09	137
44	69	6.3	8.15	1	421.90	na	0.09	51	170	11	5	2	0.2	0.01	21	<10	0.19	135
46	43	10.0	7.35	0.2	119.94	na	<0.05	17	50	4	4	2	0.3	0.01	<10	<10	0.19	99
Lake Awasa (47)	26	-	8.4	nd	307.54	na	0.13	43	170	7	7	6	nd	0.01	26	<10	0.19	95
Awasa Chem. Corp.	-	-	7.3	na	519.75	na	0.53	24	124	35	33	6	0.7	0.02	12	87	0.52	93
B.M. Hotel well	-	-	8.6	na	1019.92	na	0.55	60	416	89	55	9	0.7	0.04	90	12	0.34	59
Oasis Hotel well	-	-	8.3	na	469.19	na	0.16	23	220	30	15	5	0.1	0.1	25	24	1.30	85
Afewort Hotel well	-	-	8.4	na	632.96	na	0.17	34	330	22	10	7	0.8	0.01	41	22	0.3	71
Hotel Bellevue	-	-	8.5	na	598.42	na	0.16	28	300	22	15	7	0.7	0.01	40	21	0.76	73
River East of Awasa	-	-	7.6	na	186.40	na	0.08	16	77	10	3	3	na	na	11	<10	na	43

na = not analysed, nd = not detected

TABLE 3 Chemical composition of waters in the Lake Shalla Area (ppm)

Location	T (°C)	Flow (l/s)	pH	H <sub>2</sub> S	Total Carbonate (CO <sub>2</sub> )	NH <sub>4</sub>	Li	K	Na	Ca	Mg	F	Br	I	Cl	SO <sub>4</sub>	B	SiO <sub>2</sub>
NB 3712-																		
Lake Shalla (34)	-	-	10.15	1	6478.43	1.18	0.05	225	6800	<3	<2	300	nd	0.05	3030	137	24.2	116
29	51	1.2	9.7	0.6	898.64	1.20	<0.05	41	660	<3	<2	20	1.1	0.05	358	<10	1.41	166
30	96	33.3	8.9	1	2177.30	1.85	0.47	69	2340	<3	<2	60	11.5	0.09	1526	31	6.86	96
31	52	4.5	9.3	1	409.40	na	0.06	41	380	<3	<2	10	1.4	0.04	226	<10	0.91	149
33	53	0.5	9.6	1	1378.62	na	0.07	85	1150	<3	<2	35	1.2	0.05	532	37	2.72	164
35	71	<0.1	8.6	1	1242.47	na	0.50	62	1100	<3	5	30	2.8	0.07	668	<10	2.62	150
36	80	<0.1	8.35	1	1466.18	na	0.54	98	1280	<3	3	40	2.2	0.07	722	33	2.40	121
90	62	0.1	8.0	nd	3480	na	0.30	80	2600	4	3	95	nd	0.1	1249	24	na	193
91	70	3.0	10.1	nd	6861.80	na	0.50	110	4157	2.4	0.96	150	nd	0.1	1958	22	na	177
87	53	5	9.2	nd	1646.47	na	<0.05	70	1344	1.2	0.50	21	0.9	0.03	569	48	na	91
88	54	6	9.3	nd	1607.04	na	<0.05	70	1284	1.7	0.95	22	0.9	0.03	510	45	na	95
60	51	>6.6	8.7	1	1570.24	na	<0.05	90	1150	<3	3	20	2.2	0.03	414	61	1.58	68
65	60	3.3	8.5	0.7	1912.35	0.13	<0.05	83	970	4	15	20	nd	0.03	350	78	1.48	95
B.M. Hotel Well																		
Sha Shemene																		
-	-	-	8.0	na	123.34	na	<0.05	7	45	11	3	3	0.4	0.04	<10	12	0.41	55

TABLE 4 Chemical composition of waters in the Lake Langano Area (ppm)

NB 3712-																		
Lake Langano	-	-	9.1	na	491.37	na	<0.05	24	423	4	1	13	0.9	0.03	180	22	0.81	73
2	67	0.5	8.1	0.6	1117.19	0.71	0.55	81	826	12	4	24	2.4	0.04	453	32	3.3	123
3	60	0.2	8.2	0.6	675.64	nd	0.20	45	530	9	6	20	1.3	0.04	318	24	2.19	179
84	61	0.5	8.3	0.2	1200.33	na	0.37	45	858	3	0.24	38	0.5	0.02	339	15	1.40	141
10	96.5	11.6	9.1	0.4	545.03	na	0.45	56	750	<3	<2	14	2.6	0.06	460	262	3.30	165
12	93	2.0	8.9	0.2	559.09	na	0.46	55	735	<3	<2	14	2.6	0.06	449	247	3.38	155
5	92	0.1	8.7	0.6	429.77	0.50	1.00	39	570	<3	<2	12	1.0	0.04	272	384	3.11	168
8a	94	0.4	8.7	0.6	433.52	0.85	0.84	32	560	<3	<2	9	0.8	0.04	274	366	2.79	161
16	38	17	8	0.2	276.30	na	0.56	20	100	17	8	2	0.5	0.01	34	37	0.72	105
Lake Zwai	60	0.1	7.6	1	537.85	na	0.18	25	240	15	8	7	nd	0.02	31	<10	0.81	159
20	60	0.1	7.6	1	537.85	na	0.18	25	240	15	18	7	nd	0.02	31	<10	0.81	159
23	78	Small	8.15	2	731.45	na	0.53	38	400	8	5	5	nd	0.02	95	31	1.58	176

na = not analysed, nd = not detected

TABLE 5 Isotopic composition of waters in the Lake Abaya, Lake Awasa-Wondo Genet, Lake Shalla and Lake Langano areas

<u>Abaya</u>			<u>Langano</u>		
Location	o/oo $\delta D$	o/oo $\delta^{18}O$	Location	o/oo $\delta D$	o/oo $\delta^{18}O$
NB 37161- 6	-5.7	-0.66	NB 37121-		
8	-8.7	-2.88	Lake Langano (SW)	45	6.73
15	-9.4	-2.98	B.M. Langano well	10	0.39
16	-7.1	-2.70	Lake Zwai (Bulbula River)	39	5.29
Lake Abaya	49.6	7.25	Swai well		
Humasa River	6.2	-0.07	Adami Tulu well	32.6	4.28
			1	-0.3	-1.33
			5	-2.2	-0.87
			11	3.6	0.39
			12	2.5	-0.44
 <u>Awasa-Wondo Genet</u>			 <u>Shalla</u>		
Location	o/oo $\delta D$	o/oo $\delta^{18}O$	Location	o/oo $\delta D$	o/oo $\delta^{18}O$
NB 37121-			NB 37121-		
Wondo Genet (41)	-8.0	-2.38	Lake Shalla, surface	54.5	8.49
Kike Hot Springs (45)	-6.2	-2.47	Lake Chittu	60.3	10.48
Shallo Hot Springs (52)	-5.7	-0.47	Shalla cold spring	2.9	-1.62
Graha Quhe (4)	5.3	-0.69	Lake Abayata	64.2	10.00
Kenteri Cold Springs	-3.3	-2.06	Shashemene well	-1.4	-2.05
Kenteri Hot Springs (45)	-7.6	-3.00	30	2.4	2.5
Lake Awasa	54.5	8.25	90	1.9	-1.97
Lake Shallo	44	6.77	Shalla S-W spring	17.9	12.78
Awasa Bank Well	2.8	-1.15	Chittu hot springs	15.9	1.47
Awasa B.M. Well	34.4	4.67	Jido River	2.1	-1.89
Shashemene Well	-1.4	-2.05			

TABLE 6 Calculated temperatures (°C) from solute geothermometers for geothermal waters in Lakes District by the method of Arnorsson and Svavarsson (1985)

Sample no.	T1	T2*	T3*	T4	T5*	T6	T7	T8	T9*	T10	T11*	T12*	T13	M	δ
<b>Abaya:</b>															
NB 37161- 6	171.4	150.0	286.7	-	151	204.5	170	299	305	174	224.5	-	157	196	48
8	151.6	129.2	215.1	201	128.5	218.5	154	212	275	156	100	247	139.5	176	30
15	150.2	127.8	202.8	200	127	227	-	199.5	269.5	175	107.5	-	149.5	183	28
16	138.2	115.2	266.5	208	114	203	-	271	(382)	134.5	66	161	133	181	51
19	144.4	121.6	177.3	185	120.5	182	164.5	175	139	129	75.5	136.5	76	151	36
20	136.7	113.6	242	204	112.5	200	-	241.5	-	156.6	92.5	237	139	180	38
22	118.2	94.2	401.5	-	93.5	147	154	-	-	150	52	145.5	123	138	15
25	115.2	91.1	96.7	-	90.5	167.5	119.5	98.5	187	139.5	70.5	201.5	118.5	126	22
<b>Awasa and Wondo-Genet:</b>															
NB 37121- 4	148.8	126.3	222.6	207	125.5	190.5	151	220	265	140.5	120	203	144.5	172	31
40	138.2	115.1	217.3	206	114	201.5	133	214.5	(425.5)	135.5	134.5	148	145	168	35
44	144.9	122.2	(332.2)	256	121	178.5	132	375	199	130.5	119.5	146	123.5	191	86
52	146.2	123.5	215	-	122.5	188.5	150.5	212	(342.5)	158.5	140.5	-	143	166	25
<b>Shalla:</b>															
NB 37121-29	155.8	133.6	177.5	-	133	187.5	123.5	175	-	150	132.5	208.5	123.5	152	39
30	126.3	102.7	102.7	-	101.5	215	136	104	135.5	177	157	-	128	152	39
31	150.1	127.7	222.2	-	127	175	131.5	219.5	119	146.5	130	184.5	124	159	35
33	156.3	134.1	193.8	-	133.5	204	135	190.5	78.5	165.5	168.5	-	138	167	27
35	152.3	129.9	158.3	-	129	212	139.5	157	192.5	179.5	130.5	-	133	164	29
36	139.5	116.6	186.5	-	115.5	212.5	138	183.5	185	178.5	164	-	136.5	169	29
90	169.1	147.6	115.7	180	148.5	252	-	117	112.5	213	157.5	-	154	183	47
91	156.8	134.6	140.8	185	134	218	-	141	143	168.5	205.5	-	124	167	33
87	122.6	98.8	149.3	210	98	198.5	-	148.5	-	173	193	190	124.5	171	31
88	124.6	100.9	154.6	208	100	196.5	-	153.5	-	164.5	177	190.5	123.5	169	30
60	108.7	84.1	185.1	-	83.5	195.5	130	182.5	-	154.5	161	179	120.5	157	29
65	125.8	102.2	196.9	209	101	202.5	129	193.5	-	160	122	199.5	132.5	157	29
<b>Langano</b>															
NB 37121- 2	140.4	117.5	212.4	215	116.5	205.5	130	209	221.5	149.5	148.5	237	136	169	36
3	163.4	141.6	199.3	200	142	200.5	133	196	177	153	113	-	144	170	26
84	148.5	125.9	152.1	192	125	210	117	151.5	188	175.5	187.5	-	134.5	161	30
12	154	131.7	177.1	-	131	191	116	174.5	214	167.5	157.5	220	158.5	160	23
10	157.8	135.6	177	-	135.5	190.5	125.5	174.5	211	167	159.5	223.5	160.5	163	20
5	159.1	137.1	164.5	-	137	187.5	131.5	163	321	168	148.5	219	166	162	16
8a	156.4	134.2	147.8	-	133.5	186.5	130.5	147.5	301.5	166.5	139	202	163.5	158	17
16	130.9	107.5	283	212	106.5	166	110	293.5	-	120	75	139.5	126.5	166	61
20	155.9	133.7	219.9	192	133	194	138	217	230.5	140	82.5	193.5	133	167	31
23	161.5	139.6	277.2	203	139.5	197	145.5	285.5	370.5	146	112.5	178.5	140	183	48

\* - excluded in the calculation of mean and standard deviation for geothermal waters in Abaya, Awasa-Wando Genet and Langano Areas.

\* - and T1 excluded in the calculation of mean and standard deviation for geothermal waters in Shalla Area.

TABLE 7 Temperature functions for solute geothermometers

No.	Geothermometer	Temperature functions	Range (°C)	Source
1	Quartz	$t^{\circ}\text{C} = \frac{1164}{4.90 - \log \text{SiO}_2} - 273.15$	180-250	Arnorsson et al. (1983a); SiO <sub>2</sub> in mg/kg
2	Chalcedony	$t^{\circ}\text{C} = \frac{1101}{0.11 - \log \text{SiO}_2} - 273.15$	25-180	Arnorsson et al. (1983a); SiO <sub>2</sub> in mg/kg
3	NaK	$t^{\circ}\text{C} = \frac{933}{\log \text{Na/K} + 0.993} - 273.15$	25-250	Arnorsson et al. (1983a); Na, K in mg/kg
4	Na-K-Ca	$t^{\circ}\text{C} = \frac{1647}{\log \text{Na/K} + \beta \log \text{Ca/Na} + 2.24} - 273.15$	4-340	Fournier and Truesdell (1973); $\beta = 1/3$ for $\sqrt{\text{Ca/Na}} < 1$ and $T_{\text{H}}/3 > 100^{\circ}\text{C}$ . Na, K, Ca in moles/l
5	SiO <sub>2</sub>	$\log^m \text{H}_4\text{SiO}_4 = -0.588 - 0.00441T - 1515.21/T + 1.3470 \cdot \log T$		Arnorsson et al. (1983b)
6	CO <sub>2</sub>	$\log^m \text{H}_2\text{CO}_3 = -1.794 - 0.00510T - 4469.63/T + 4.1414 \cdot \log T$		Arnorsson et al. (1983b)
7	H <sub>2</sub> S	$\log^m \text{H}_2\text{S} = -1.678 - 0.00355T - 5071.05/T + 3.8889 \cdot \log T$		Arnorsson et al. (1983b)
8	NaK	$\log^a \text{Na}^+/\text{aK}^+ = -1.782 - 2775.5/T + 558780/T^2 - 0.00969T + 4.104 \cdot \log T$		Arnorsson and Svavarsson (1985)
9	Na/Li	$\log^a \text{Na}^+/\text{aLi}^+ = 0.161 + 1201/T$		Arnorsson and Svavarsson (1985)
10	CaH	$\log^a \sqrt{\text{Ca}^{2+}/\text{aH}^+} = -1.733 + 0.01117T + 3890.51/T - 3.9977 \cdot \log T$		Arnorsson et al. (1983b)
11	MgK	$\log^a \sqrt{\text{Mg}^{2+}/\text{aK}^+} = -0.00396T + 978.33/T$		Arnorsson and Svavarsson (1985)
12	HF	$\log^m \text{HF} = -5.262 - 0.03511T - 7964.11/T + 12.1022 \cdot \log T$		Arnorsson et al. (1985)
13	H <sub>2</sub> SO <sub>4</sub>	$\log^m \text{H}_2\text{SO}_4 = -6.436 - 0.03906T - 13335.68/T + 14.7958 \cdot \log T$		Arnorsson et al. (1983b)

TABLE 8 Gas analyses results from Lake Langano, Corbetti and Lade Abaya areas (mM/kg)

Location	Sample no.	Discharge T(°C)	CO <sub>2</sub>	H <sub>2</sub> S	NH <sub>3</sub>	H <sub>2</sub>	O <sub>2</sub>	N <sub>2</sub>	CH <sub>4</sub>	Excess N <sub>2</sub>	Corrected N <sub>2</sub>
<u>Langano</u> NB 37121-											
Bobesa	28	91.5	683.25	0.12	0.06	nd	496.11	1857.74	0.79	8.81	1848.93
*Gebiba	24	95	344.98	0.30	0.26	0.16	0.09	2.17	0.90	1.82	0.35
*Gebiba	24	95	305.56	0.19	0.24	0.09	0.01	1.76	0.67	1.72	0.04
Finkilo	19	92.5	1547.17	0.13	0.09	trace	8.65	32.46	8.21	0.22	32.24
Kure	49	-	219.44	0.18	0.23	trace	497.37	1870.45	nd	16.30	1854.15
Aluto B	-	85	2499.97	0.67	0.02	nd	4086.74	15780.92	12.98	546.10	15234.82
Auto	27	95	564.57	0.28	0.77	trace	44.82	183.5	4.95	16.62	166.88
*Hulo	26	93	146.67	0.56	2.28	nd	498.44	1880.23	0.63	22.25	1857.98
*Hulo	26	93.5	211.08	0.38	2.11	na	na	na	na	na	-
<u>Corbetti</u> NB 37121-											
Koka	56	95	1152.78	0.08	0.67	0.13	2.69	28.69	10.28	18.65	10.04
Doredimtu	54	92.5	670.05	nd	0.67	nd	1222.73	4693.04	nd	253.53	4439.51
Chebicha	74	90.5	749.97	nd	na	nd	1567.36	6109.33	nd	264.60	5844.73
Danshe	70	85.5	555.54	nd	na	nd	2002.10	7728.18	1.95	266.45	7461.73
Borama	76	95	519.48	nd	0.39	nd	51.75	216.71	0.55	23.67	193.04
Borama	76	95	561.20	nd	0.44	nd	112.99	433.14	nd	11.96	421.18
Demo Argo	79	95	605.58	nd	0.22	nd	1380.42	5310.11	nd	165.62	5144.49
<u>Abaya</u> NB 37161-											
Abaya F	7a	95.5	3572.06	2.38	0.72	0.11	6.42	15.58	10.48	-	-
Digima	22	96.5	738.92	nd	0.09	0.007	0.17	15.43	1.81	14.02	0.61

\* and \* the same fumarole at different time.



TABLE 9 Estimated temperatures from gas geothermometers for the Lake Langano, Corbetti and Lake Abaya areas (°C)

Location	Sample no.	Discharge T(°C)	TCO <sub>2</sub>	TH <sub>2</sub> S	TCO <sub>2</sub> /N <sub>2</sub>	TCO/H <sub>2</sub>	TH <sub>2</sub> S/H <sub>2</sub>	TH <sub>2</sub>	T <sup>1</sup> CO <sub>2</sub> /N <sub>2</sub>
<u>Langano</u> NB 37121~									
Bobessa	28	91.5	318	205	124	~	~	~	124
Gebiba	24	95	300	223	295	246	293	260	337
Gebiba	24	95	296	214	297	241	241	255	361
Finkilo	19	92.5	341	207	260	~	~	~	261
Kure	49	~	287	213	105	~	~	~	105
Aluto B	~	85	357	239	109	~	~	~	110
Auto	27	95	313	222	178	~	~	~	180
Hulo	26	93	275	235	100	~	~	~	100
Hulo	26	93.5	286	228	~	~	~	~	~
<u>Corbetti</u> NB 37121~									
Koka	56	95	333	333	255	229	312	259	286
Doredimtu	54	92.5	318	318	107	~	~	~	108
Chebicha	74	90.5	321	321	105	~	~	~	106
Danshe	70	85.5	313	313	99	~	~	~	~
Borama	76	95	311	311	171	~	~	~	~
Borama	76	95	313	313	154	~	~	~	~
Demo Argo	79	95	315	315	104	~	~	~	~
<u>Abaya</u> NB 37161~									
Abaya F	7a	95.5	369	369	305	213	251	257	~
Duguna	22	96.5	320	~	261	198	~	232	~

-T<sup>1</sup> CO<sub>2</sub>/N<sub>2</sub>: Corrected for excess N<sub>2</sub>  
 ~ and \* The same fumarole at different time

TABLE 10 Temperature function for gas geothermometers

Geothermometer	Temperature function	Restriction
CO <sub>2</sub>	$- 44.1 + 269.25Q - 76.88Q^2 + 9.52Q^3$	All waters
H <sub>2</sub> S	$+ 246.7 + 44.81Q$	All waters
H <sub>2</sub>	$+ 277.2 + 20.99Q$	above 300°C
CO <sub>2</sub> /H <sub>2</sub>	$+ 341.7 - 28.57Q$	and waters in
H <sub>2</sub> S/H <sub>2</sub>	$+ 304.1 - 39.48Q$	the range 200-300°C
		if chloride >500 ppm

Source: Arnorsson and Gunnlaugsson, 1985

Appendix I Sampling and analytical methods adopted for geothermal fluids

Component	Sample treatment	Method
pH	Raw, untreated, cooled	Instrumental (pH-meter)
CO <sub>2</sub>	Raw, untreated, cooled	Titration with HCl (using pH-meter to mark end point)
H <sub>2</sub> S	Raw, untreated, cooled	Titration with Mercuric Acetate (using dithizone as indicator)
Cl	Filtered, untreated	Chloride meter
F	Filtered, untreated	Selective electrode
SiO <sub>2</sub>	Raw, untreated,	Diluted UV/VIS spectrophotometry (Silico-molybdate complex)
B	Filtered, untreated	UV/VIS Spectrophotometry (Methylene blue complex)
SO <sub>4</sub>	Raw, untreated should be precipitated	(Sulfide titration with Barium perchlorate by zinc acetate)
Na and K	Filtered, acidified	A.A. Spectrophotometry (with lanthanum as inhibitor to interference)
Dissolved solids	Raw, untreated	Evaporated residue
Gases	Raw, untreated (alkaline condensation and/or without condensation)	Gas chromatography, titration
Isotope	Raw, untreated	Mass Spectrophotometer

APPENDIX II Equations describing the temperature dependence of mineral solubilities.

MINERAL	REACTION	TEMPERATURE FUNCTION (°K)
401 ADULARIA <sup>c</sup>	$KAlSi_3O_8 + 8H_2O = K^+ + Al(OH)_4^- + 3H_4SiO_4^0$	+38.85 -0.0458T -17260/T +1012722/T <sup>2</sup>
402 LOW-ALBITE	$NaAlSi_3O_8 + 8H_2O = Na^+ + Al(OH)_4^- + 3H_4SiO_4^0$	+36.83 -0.0439T -16474/T +1004631/T <sup>2</sup>
403 ANALCIME	$NaAlSi_2O_6 \cdot H_2O + 5H_2O = Na^+ + Al(OH)_4^- + 2H_4SiO_4^0$	+34.08 -0.0407T -14577/T +970981/T <sup>2</sup>
404 ANHYDRITE	$CaSO_4 = Ca^{+2} + SO_4^{-2}$	+6.20 -0.0229T -1217/T
405 CALCITE <sup>d</sup>	$CaCO_3 = Ca^{+2} + CO_3^{-2}$	+10.22 -0.0349T -2476/T
406 CHALCEDONY <sup>e</sup>	$SiO_2 + 2H_2O = H_4SiO_4^0$	+0.11 -1101/T
407 Mg-CHLORITE	$Mg_5Al_2Si_3O_{10}(OH)_8 + 10H_2O = 5Mg^{+2} + Al(OH)_4^- + 3H_4SiO_4^0 + 8OH^-$	-1022.12 -0.3861T +9363/T +412.461logT
408 FLUORITE <sup>f</sup>	$CaF_2 = Ca^{+2} + 2F^-$	+66.54 -4318/T -25.47logT
409 GOETHITE <sup>g</sup>	$FeOOH + H_2O + OH^- = Fe(OH)_4^-$	-80.34 +0.099T +20290/T -2179296/T <sup>2</sup>
410 LAUMONTITE	$CaAl_2Si_4O_{12} \cdot 4H_2O + 8H_2O = Ca^{+2} + 2Al(OH)_4^- + 4H_4SiO_4^0$	+65.95 -0.0828T -28358/T +1916098/T <sup>2</sup>
411 MICROCLINE	$KAlSi_3O_8 + 8H_2O = K^+ + Al(OH)_4^- + 3H_4SiO_4^0$	+44.55 -0.0498T -19883/T +1214019/T <sup>2</sup>
412 MAGNETITE	$Fe_3O_4 + 4H_2O = 2Fe(OH)_4^- + Fe^{+2}$	-155.58 +0.1658T +35298/T -4258774/T <sup>2</sup>
413 Ca-MONTMOR <sup>c</sup>	$6Ca_{0.167}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + 60H_2O + 12OH^- = Ca^{+2} + 14Al(OH)_4^- + 22H_4SiO_4^0$	+30499.49 +3.5109T -1954295/T +125536640/T <sup>2</sup> -10715.661logT
414 K-MONTMOR <sup>c</sup>	$3K_{0.33}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + 30H_2O + 6OH^- = K^+ + 7Al(OH)_4^- + 11H_4SiO_4^0$	+15075.11 +1.7346T -967127/T +61985927/T <sup>2</sup> -5294.721logT
415 Mg-MONTMOR <sup>c</sup>	$6Mg_{0.167}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + 60H_2O + 12OH^- = Mg^{+2} + 14Al(OH)_4^- + 22H_4SiO_4^0$	+30514.87 +3.5188T -1953843/T +125538830/T <sup>2</sup> -10723.711logT
416 Na-MONTMOR <sup>c</sup>	$3Na_{0.33}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + 30H_2O + 6OH^- = Na^+ + 7Al(OH)_4^- + 11H_4SiO_4^0$	+15273.90 +1.7623T -978782/T +62805036/T <sup>2</sup> -5366.181logT
417 MUSCOVITE	$KAl_3Si_3O_{10}(OH)_2 + 10H_2O + 2OH^- = K^+ + 3Al(OH)_4^- + 3H_4SiO_4^0$	+6113.68 +0.6914T -394755/T +25226323/T <sup>2</sup> -2144.771logT
418 PREHNITE	$Ca_2Al_2Si_3O_{10}(OH)_2 + 10H_2O = 2Ca^{+2} + 2Al(OH)_4^- + 2OH^- + 3H_4SiO_4^0$	+90.53 -0.1298T -36162/T +2511432/T <sup>2</sup>
419 PYRRHOTITE	$8FeS + SO_4^{-2} + 22H_2O + 6OH^- = 8Fe(OH)_4^- + 9H_2S$	+3014.68 +1.2522T -103450/T -1284.861logT
420 PYRITE	$8FeS_2 + 26H_2O + 10OH^- = 8Fe(OH)_4^- + SO_4^{-2} + 15H_2S$	+4523.89 +1.6002T -180405/T -1860.331logT
421 QUARTZ <sup>h</sup>	$SiO_2 + 2H_2O = H_4SiO_4^0$	+0.41 -1309/T (0-250°C); +0.12 -1164/T (180-300°C)
422 WAIRAKITE	$CaAl_2Si_4O_{12} \cdot 2H_2O + 10H_2O = Ca^{+2} + 2Al(OH)_4^- + 4H_4SiO_4^0$	+61.00 -0.0847T -25018/T +1801911/T <sup>2</sup>
423 WOLLASTONITE	$CaSiO_3 + 2H^+ + H_2O = Ca^{+2} + H_4SiO_4^0$	-222.85 -0.0337T +16258/T -671106/T <sup>2</sup> +80.681logT
424 ZOISITE	$Ca_2Al_3Si_3O_{12}(OH) + 12H_2O = 2Ca^{+2} + 3Al(OH)_4^- + 3H_4SiO_4^0 + OH^-$	+106.61 -0.1497T -40448/T +3028977/T <sup>2</sup>
425 EPIDOTE	$Ca_2FeAl_2Si_3O_{12}(OH) + 12H_2O = 2Ca^{+2} + Fe(OH)_4^- + 2Al(OH)_4^- + 3H_4SiO_4^0 + OH^-$	-27399.84 -3.8749T +1542767/T -92778364/T <sup>2</sup> +9850.381logT
426 MARCASITE <sup>i</sup>	$8FeS_2 + 26H_2O + 10OH^- = 8Fe(OH)_4^- + SO_4^{-2} + 15H_2S$	+4467.61 +1.5879T -169944/T -1838.451logT

<sup>a</sup>If not otherwise specified data for minerals and aqueous species are from HELGESON et al. (1978) and HELGESON (1969). <sup>b</sup>Data on  $Al(OH)_4^-$  and  $Fe(OH)_4^-$  are from ARNORSSON et al. (1982a) and GUNNLAUGSSON and ARNORSSON (1982) respectively. <sup>c</sup>Thermodynamic data on adularia are from HELGESON (1969). <sup>d</sup>Data on the enthalpy and entropy of calcium ion at 25°C are from ROBIE et al. (1978). <sup>e</sup>ARNORSSON et al. (1982b). Their empirical solubility function is very similar to the experimental solubility data of FOURNIER (1977). <sup>f</sup>NORDSTROM and JENNE (1977). <sup>g</sup>LANGMUIR (1971). <sup>h</sup>MOREY et al. (1962), KENNEDY (1950). <sup>i</sup>NAUMOV et al. (1971).

Appendix III: Samples of computer printout of the WATCH 2 programme.

ORNUSTOFHIM .JHD  
1985-07-29 Berhan

ababa

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0037468		ARRIVA18		ETHIOPIA		LAKES		ACTIVITY COEFFICIENTS IN DEEP WATER	
PROGRAM WATCH2.									
WATER SAMPLE (PPH)									
PH/DEG.C	7.70/ 0.0	GAS (VOL.%)		REFERENCE TEMP.		DEGREES C		0.0 (RTZ)	
SI02	146.00	CO2		SAMPLING PRESSURE		BARS ABS.		0.0/ 0.0	
NA	500.00	H2S		DISCHARGE ENTHALPY		KJ/MOL/KG		0.0/ 0.0	
K	50.00	O2		DISCHARGE		KG/SET.		0.0	
CA	20.00	CH4		MEASURED TEMPERATURE		DEGREES C		65.5	
MG	14.000	H2		RESISTIVITY/TEMP.		OHM/CM.C		0.0/ 0.0	
CO2	1059.72			EN/TEMP.		MV/DEG.C		0.000/ 0.0	
S04	12.00								
CL	48.00								
F	13.00								
LITERS GAS PER KG									
CONDENSATE/DEG.C									
CO2	0.0000								
B	0.7000								
FE	0.0000								
MH3	0.1800								

CHEMICAL COMPONENTS IN DEEP WATER (PPM AND LOG MOLE)									
HI (ACT.)	0.00	-7.312	NIH1	9.28	-3.418	FE(OH)3	0.00	0.000	0.000
OH-	1.15	-4.169	NAFL	0.54	-5.034	FE(OH)4-	0.00	0.000	0.000
MHS104	222.13	-2.636	KCL	0.02	-6.444	FEL1	0.00	0.005	0.005
H2S104-	9.49	-4.001	MSD14-	0.87	-5.135	FEL2	0.00	0.000	0.000
H2S104--	0.00	-7.392	MSB14-	0.79	-5.666	FEL11	0.00	0.000	0.000
MHS104	2.26	-4.718	CASD4	0.28	-5.691	FEL21	0.00	0.000	0.000
H2S104-	3.88	-4.202	H2SD4	3.00	-4.603	FEL3	0.00	0.000	0.000
H2S104--	0.12	-5.712	CACD3	4.57	-4.340	FEL4-	0.00	0.000	0.000
H2CO3	261.79	-2.375	MHC03	1.99	-4.628	FESD4	0.00	0.000	0.000
HCO3-	1177.43	-1.715	CANCD31	33.19	-3.484	FESD41	0.00	0.000	0.000
CO3--	1.85	-4.511	MHC031	11.48	-3.871	ALH1	0.00	0.000	0.000
H2S	0.32	-5.031	CAHH	0.02	-6.517	ALOH1	0.00	0.000	0.000
HS-	1.43	-4.307	MGRH	0.46	-4.957	AL(OH)21	0.00	0.000	0.000
S--	0.00	-12.301	MH4OH	0.32	-5.040	AL(OH)3	0.00	0.000	0.000
H2SO4	0.00	-16.588	MH4	0.03	-5.838	AL(OH)4-	0.00	0.000	0.000
HSO4-	0.00	-7.821	FEH	0.00	0.000	ALSD4	0.00	0.000	0.000
SO4--	8.50	-4.053	FEH1	0.00	0.000	ALSD412-	0.00	0.000	0.000
HF	0.01	-6.169	FEH11	0.00	0.000	ALF1	0.00	0.000	0.000
F-	12.99	-3.185	FE(OH)2	0.00	0.000	ALF21	0.00	0.000	0.000
CL-	47.66	-2.871	FE(OH)3-	0.00	0.000	ALF3	0.00	0.000	0.000
NAH	499.18	-1.663	FE(OH)4--	0.00	0.000	ALF4-	0.00	0.000	0.000
K1	49.90	-2.894	FE(OH)11	0.00	0.000	ALF5--	0.00	0.000	0.000
CAH1	4.92	-3.911	FE(OH)21	0.00	0.000	ALF6---	0.00	0.000	0.000

IONIC STRENGTH = 0.02375		IONIC BALANCE :	
CATIONS (MOL.EQ.10.02447368)		ANIONS (MOL.EQ.10.02178138)	
DIFFERENCE (Z) 11.61		DIFFERENCE (Z) 11.61	
1000/T DEGREES KELVIN = 2.33			

CHEMICAL GEOTHERMOMETERS DEGREES C									
QUARTZ	156.6								
CHA.CEDONY	127.8								
NAK	198.6								

OXIDATION POTENTIAL (VOLTS) :									
EH H2S= -0.481		EH CH4= 99.999		EH H2= 99.999		EH HHS= 99.999		EH HNS= 99.999	

LOG SOLUBILITY PRODUCTS OF MINERALS IN DEEP WATER									
AMALGAM	-15.313	99.999	ALBITE LIM	-14.931	99.999	ANALCIME	-17.014	99.999	TEOR. CALC.
ANTHYRITE	-6.474	-8.656	CALCITE	-10.539	-9.106	CHA.CEDONY	-2.452	-2.436	
MS-CHAURITE	-80.163	99.999	FLUORITE	-10.576	-10.758	GROTHITE	-2.483	99.999	
LAURITE	-25.246	99.999	MICROCLIN	-16.545	99.999	MAGNETITE	-25.254	99.999	
CA-MONTHMOR.	-76.133	99.999	K-MONTHMOR.	-36.399	99.999	MG-MONTHMOR.	-77.497	99.999	
NA-MONTHMOR.	-36.560	99.999	MUSCOVITE	-18.817	99.999	PREHNITE	-35.800	99.999	
PHYRROPHILITE	-71.240	99.999	PYRITE	-106.890	99.999	QUARTZ	-2.436	-2.436	
WATERKALTE	-23.859	99.999	MOLLASITOMITE	9.314	7.746	ZOISITE	-35.442	99.999	
EPIDOTE	-39.348	99.999	MARCASITE	-86.497	99.999				

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00370021 ANASHA-CHEK.CDR LAKES ETHIOPIA

PROGRAM WATCH2.

WATER SAMPLE (PPM) STEAM SAMPLE

PH/DEG.C 7.30/ 0.0 GAS (VOL.%)  
 SI02 93.00 CO2  
 NA 124.00 H2S  
 K 24.00 H2  
 CA 35.00 CH4  
 HG 33.0000 CH4  
 CO2 519.75 H2  
 SO4 87.00  
 H2S 0.00  
 CL 12.00  
 F DISS.SOLIDS  
 AL 0.0000  
 B 0.5200  
 FE 0.0000  
 NH3 0.0000

LITERS GAS PER KG  
 CONDENSATE/DEG.C  
 CONDENSATE (PPM)  
 PH/DEG.C  
 CO2  
 H2S  
 NA

CONDENSATE WITH NAH3 (PPH)  
 CO2  
 H2S

MEASURED DOWNHOLE TEMP. FLUID INFLOW  
 DEGREES C/METERS DEPTH (METERS)

MEASURED TEMPERATURE DEGREES C 0.0  
 RESISTIVITY/TEMP. OHM/DEG.C 0.0/ 0.0  
 EN/TEMP. MV/DEG.C 0.000/ 0.0

IONIC BALANCE : CATIONS (MOL.EQ./0.01022637  
 ANIONS (MOL.EQ./0.01242221  
 DIFFERENCE (Z) -19.39

DEEP WATER (PPH) DEEP STEAM (PPH) GAS PRESSURES (BAR ABS.)

SI02 93.01 CO2 519.75 CO2 0.00 CO2 0.223E+00  
 NA 124.00 H2S 0.00 H2S 0.00 H2S 0.000E+00  
 K 24.00 H2 0.00 H2 0.00 H2 0.000E+00  
 CA 35.00 O2 0.00 O2 0.00 O2 0.000E+00  
 HG 32.997 CH4 0.00 CH4 0.00 CH4 0.000E+00  
 SO4 87.00 H2 0.00 H2 0.00 H2 0.000E+00  
 CL 12.00 NH3 0.00 NH3 0.00 NH3 0.000E+00  
 F 6.00 H2O 0.283E+01  
 DISS.S. 0.00 TOTAL 0.304E+01  
 AL 0.0000  
 B 0.5200  
 FE 0.0000 H2O (Z) 0.00  
 BOILING POINT 0.00

ACTIVITY COEFFICIENTS IN DEEP WATER

HA	0.883	NSO4--	0.871	FEH	0.583	FECL+	0.865
OH-	0.863	F-	0.863	FEH+	0.329	ALH+	0.329
H2S(OH-	0.865	CL-	0.861	FEH+	0.869	ALOH	0.577
H2S(OH--	0.577	NAH	0.865	FE(OH)3-	0.869	AL(OH)2+	0.871
H2RO3-	0.859	K+	0.861	FE(OH)4--	0.573	AL(OH)4-	0.867
HCO3-	0.865	CAH+	0.583	FEH+	0.573	ALSO4+	0.867
CO3--	0.548	H2H+	0.601	FE(OH)2+	0.871	AL(SO4)2--	0.867
HS-	0.883	CH(OH)3+	0.873	FE(OH)4-	0.871	ALF+	0.577
S--	0.865	H(OH)3+	0.865	FESO4	0.869	ALF2+	0.871
HSO4-	0.867	CAOH+	0.873	FECL+	0.573	ALF4-	0.867
SO4--	0.562	NSOH+	0.875	FECL2-	0.869	ALF5--	0.548
NSO4-	0.871	NAH	0.859	FECL4-	0.865	ALF6---	0.280

CHEMICAL COMPONENTS IN DEEP WATER (PPM AND LOG MOLE)

HA (ACT.)	0.00	-7.232	H2H+	20.85	-3.047	FE(OH)3	0.00	0.000
OH-	0.50	-4.535	NAH	0.03	-6.296	FE(OH)4-	0.00	0.000
H2S(OH-	144.18	-2.824	KCL	0.00	-7.673	FECL+	0.00	0.000
H2S(OH--	4.32	-4.343	NSO4-	1.20	-4.997	FFCL2	0.00	0.000
H2RO3-	0.00	-7.863	K2SO4	0.74	-5.259	FECLH+	0.00	0.000
HCO3-	0.28	-5.627	CAH+	5.32	-4.408	FECL2+	0.00	0.000
CO3--	2.90	-4.328	H2SO4	39.64	-3.482	FECL3	0.00	0.000
HS-	0.07	-5.943	CAH3+	4.91	-4.309	FECL4-	0.00	0.000
H2CO3	109.74	-2.752	NSO4	1.89	-4.650	FESO4	0.00	0.000
HCO3-	575.69	-2.025	CAHCO3+	38.54	-3.419	FESO4+	0.00	0.000
CO3--	0.86	-4.844	H(OH)3+	11.88	-3.856	ALH+	0.00	0.000
H2S	0.00	0.000	CAOH+	0.02	-6.414	AL(OH)2+	0.00	0.000
HS-	0.00	0.000	NSOH+	0.36	-5.057	AL(OH)3	0.00	0.000
S--	0.00	0.000	NAOH	0.09	0.000	AL(OH)3	0.00	0.000
H2SO4	0.00	-16.145	NAH+	0.00	0.000	AL(OH)4-	0.00	0.000
HSO4-	0.01	-7.258	FEH+	0.00	0.000	ALSO4+	0.00	0.000
SO4--	50.11	-3.283	FEH+	0.00	0.000	AL(SO4)2--	0.00	0.000
HF	0.00	-6.649	FE(OH)2	0.00	0.000	ALF+	0.00	0.000
F-	6.00	-3.501	FE(OH)3-	0.00	0.000	ALF2+	0.00	0.000
CL-	11.98	-3.471	FE(OH)4--	0.00	0.000	ALF3	0.00	0.000
NA+	123.70	-2.269	FE(OH)4--	0.00	0.000	ALF4-	0.00	0.000
K+	23.78	-3.216	FE(OH)H+	0.00	0.000	ALF5--	0.00	0.000
CAH+	16.18	-3.394	FE(OH)2+	0.00	0.000	ALF6---	0.00	0.000

IONIC BALANCE : CATIONS (MOL.EQ./0.00904091 -  
 ANIONS (MOL.EQ./0.01123574  
 DIFFERENCE (Z) -21.65

CHEMICAL GEOTHERMOMETERS DEGREES C 1000/T DEGREES KELVIN = 2.47

QUARTZ 131.6  
 CHALCEDONY 103.1  
 NAK 280.0

OXIDATION POTENTIAL (VOLTS) : EH H2S= 99.999 EH CH4= 99.999 EH H2= 99.999 EH NH3= 99.999

LOG SOLUBILITY PRODUCTS OF MINERALS IN DEEP WATER

ABURATA	-16.149	99.999	ALBITE LOW	-15.507	99.999	ANALCIME	-12.481	99.999
ANHYDRITE	-6.076	-7.161	CALCITE	-10.024	-8.718	CHALCEDONY	-2.610	-2.824
HG-CHLORITE	-79.901	99.999	FLUORITE	-10.533	-10.758	GOETHITE	-3.442	99.999
LAURONTITE	-23.929	99.999	HYDROCLINE	-17.319	99.999	MAGNETITE	-27.237	99.999
CA-MONTHOR.	-79.301	99.999	K-MONTHOR.	-38.203	99.999	HG-MONTHOR.	-80.582	99.999
NA-MONTHOR.	-38.308	99.999	MUSCOVITE	-19.611	99.999	PREHNITE	-36.020	99.999
PYRRHOTITE	-83.940	99.999	PYRITE	-124.360	99.999	QUARTZ	-2.824	-2.824
WARRKITE	-24.094	99.999	MOLLASTONITE	9.929	8.011	ZOLSITE	-35.425	99.999
EPIDOTE	-41.102	99.999	MARCASITE	-102.729	99.999			



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LAM,84 LAKES ETHIOPIA

ACTIVITY COEFFICIENTS IN DEEP WATER

H+	0.822	KS04-	0.794	FEH+	0.414	FECL+	0.781
DH-	0.775	F-	0.775	FEH+	0.178	ALH+	0.178
HS104-	0.781	CL-	0.770	FEDH+	0.790	AL(OH)2+	0.403
HS104--	0.403	NH+	0.781	FE(OH)3-	0.794	AL(OH)4-	0.786
H2003-	0.764	K+	0.770	FE(OH)4--	0.395	AL(SO4)4-	0.786
HCO3--	0.781	CAH+	0.414	FEDH+	0.395	AL(SO4)2-	0.786
CO3--	0.386	HS+	0.799	FE(OH)2+	0.794	AL(SO4)2-	0.786
HS-	0.375	CAHCO3+	0.799	FE(OH)4-	0.794	ALF+	0.403
S--	0.395	HSO3+	0.781	FES04+	0.794	ALF2+	0.794
HS04-	0.786	CAH+	0.799	FEDH+	0.395	ALF4-	0.786
S04-	0.376	HS04-	0.804	FEDH+	0.790	ALF5--	0.386
HS04-	0.794	NH4+	0.764	FEDH+	0.781	ALF6---	0.118

CHEMICAL COMPONENTS IN DEEP WATER (PPM AND LOG MOLE)

H+	0.00	-7.929	HS+	0.13	-5.258	FE(OH)3	0.00	0.000
DH-	3.84	-3.446	NHCL	5.37	-4.037	FE(OH)4-	0.00	0.000
HS104	182.80	-2.721	KCL	0.08	-5.938	FEDH+	0.60	0.000
HS104-	32.56	-3.465	HS04-	1.73	-4.039	FEDH+	0.00	0.000
HS104--	0.06	-6.182	KS04-	0.30	-5.059	FEDH+	0.00	0.000
MAHS104	12.03	-3.992	CASO4	0.03	-6.615	FEDH+	0.00	0.000
HS103	7.05	-3.943	MSO4	0.04	-6.444	FEDH+	0.00	0.000
H2003-	0.94	-4.811	CAO3	2.16	-4.667	FEDH+	0.00	0.000
HCO3-	67.03	-2.966	HSO3+	0.13	-5.824	FEDH+	0.00	0.000
HCO3--	1580.90	-1.587	CAHCO3+	3.80	-4.425	FES04+	0.60	0.000
CO3--	13.26	-3.652	HSO3+	0.18	-5.679	ALH+	0.00	0.000
H2S	0.01	-6.651	CAOH+	0.01	-7.024	ALOH+	0.00	0.000
HS-	0.19	-5.248	NH4H+	0.02	-6.408	AL(OH)2+	0.00	0.000
S--	0.00	-17.681	NH4H+	0.00	0.000	AL(OH)3	0.00	0.000
HS04-	0.60	-17.967	NH4+	0.00	0.000	AL(OH)4-	0.00	0.000
S04--	0.00	-8.465	FEH+	0.00	0.000	ALS04+	0.00	0.000
S04--	13.34	-3.857	FEH+	0.00	0.000	AL(SO4)2-	0.60	0.000
HF	0.01	-6.457	FEDH+	0.00	0.000	ALF+	0.00	0.000
F-	38.00	-2.699	FE(OH)2	0.00	0.000	ALF2+	0.00	0.000
CL-	335.67	-2.024	FE(OH)3-	0.00	0.000	ALF3	0.00	0.000
NH+	853.21	-1.430	FE(OH)4--	0.00	0.000	ALF4-	0.00	0.000
K+	44.87	-2.940	FE(OH)4--	0.00	0.000	ALF5--	0.00	0.000
CAH+	0.62	-4.814	FE(OH)2+	0.60	0.000	ALF6---	0.00	0.000

IONIC STRENGTH = 0.03890 IONIC BALANCE : CATIONS (MIL. EQ./L) 0.03834180  
ANIONS (MIL. EQ./L) 0.03849065  
DIFFERENCE (Z) -0.91

CHEMICAL GEOTHERMOMETERS DEGREES C 1000/T DEGREES KELVIN = 2.39

QUARTZ 144.9  
CHALCEDONY 115.8  
NAK 138.6

OXIDATION POTENTIAL (VOLTS) : EH H2S = -0.506 EH CH4 = 99.999 EH H2 = 99.999 EH NH3 = 99.999

LOG SOLUBILITY PRODUCTS OF MINERALS IN DEEP WATER

ARHAPTA	TEOR.	CALC.	TEOR.	CALC.				
ARHAPTA	-15.287	99.999	ALBITE LUM	-15.179	99.999	AMALCINE	-12.247	99.999
ANHYDRITE	-6.385	9.480	CALCITE	-10.294	-9.263	CHALCEDONY	-2.523	-2.721
AR-CHLORITE	-79.981	99.999	FLUORITE	-10.552	-10.816	GOETHITE	-2.866	99.999
LAURONTITE	-25.533	99.999	MICROCLINE	-16.882	99.999	MAGNETITE	-26.176	99.999
CA-MONTMOR.	-77.454	99.999	K-MONTMOR.	-37.149	99.999	MG-MONTMOR.	-78.760	99.999
NA-MONTMOR.	-37.286	99.999	MUSCOVITE	-19.143	99.999	PREHNITE	-35.864	99.999
PYRRHOTITE	-77.179	99.999	PYRITE	-114.956	99.999	QUARTZ	-2.721	99.999
WATRAMITE	-23.942	99.999	WOLLASTONITE	9.591	7.940	ZOISITE	-35.394	99.999
EPIDOTE	-40.129	99.999	MARCASSITE	-94.045	99.999			

PH/DEG.C	8.30/0.0	GAS (VOL.%)	DEGREES C	0.0 (RTZ)
SI02	141.00	CO2	DEGREES C	0.0 (RTZ)
NA	858.00	H2S	BARS ABS.	
K	45.00	H2	KG/ML/KG	
CA	3.00	O2	MG/SEC.	0.0
MS	0.240	CH4	MEASURED TEMPERATURE DEGREES C	61.0
CO2	1200.33	N2	RESISTIVITY/TEMP. OHM/DEG.C	0.0/0.0
S04	15.00		EH/TEMP.	0.000/0.0
H2S	0.20			
CL	339.00	LITERS GAS PER KG	MEASURED BOWHOLE TEMP.	FLUID INFLOW
F	38.00	CONDENSATE/DEG.C	DEGREES C/METERS	DEPTH (METERS)
DISS.SOLIDS	0.00			
AL	0.0000	CONDENSATE (PPM)		
B	1.4000	PH/DEG.C		
FE	0.0000			
NH3	0.0000			

CONDENSATE WITH NAOH (PPM)		DEEP STEAM (PPM)		GAS PRESSURES (BARS ABS.)
CO2	1200.33	CO2	0.00	CO2 0.144E+00
H2S	0.20	H2S	0.00	H2S 0.978E-05
		H2	0.00	H2 0.000E+00
		O2	0.00	O2 0.000E+00
		CH4	0.00	CH4 0.000E+00
		N2	0.00	N2 0.000E+00
		NH3	0.00	NH3 0.000E+00
		TOTAL		TOTAL 0.415E+01
				0.426E+01

IONIC STRENGTH = 0.03923 IONIC BALANCE : CATIONS (MIL. EQ./L) 0.03861149  
ANIONS (MIL. EQ./L) 0.03896673  
DIFFERENCE (Z) -0.92

SI02	141.01	CO2	1200.33	CO2	0.00	CO2	0.144E+00
NA	858.00	H2S	0.20	H2S	0.00	H2S	0.978E-05
K	45.00	H2	0.00	H2	0.00	H2	0.000E+00
CA	3.00	O2	0.00	O2	0.00	O2	0.000E+00
MS	0.240	CH4	0.00	CH4	0.00	CH4	0.000E+00
S04	15.00	N2	0.00	N2	0.00	N2	0.000E+00
CL	338.97	NH3	0.00	NH3	0.00	NH3	0.000E+00
F	38.00						
DISS.S.	0.00						
AL	0.0000						
B	1.3999						
FE	0.0000						

H2O (Z) 0.00  
BOILING PORTION 0.00