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CHEMICAL AND ISOTOPIC STUDIES ON FOUR GEOTHERMAL PROSPECTS IN THE SOUTHERN AFAR REGION, ETHIOPIA

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ABSTRACT

Isotopic and chemical studies have been carried out in Wonji, Fantale, Dofan and Meteka geothermal prospects in the Southern Afar region, Ethiopian Rift Valley. Previous studies have mostly been overviews of a big region and not very detailed, whereas this study is focussed on a relatively small area. Deuterium, tritium and oxygen-18 proved to be most important for separating different groundwater systems. Based on the isotopic data, the following three groundwater systems are identified: 1) Wonji area, 2) Fantale and Meteka area and 3) Dofan groundwater system. Tritium results show that the waters studied are not contaminated with waters from the hydrogen-bomb tests performed during the 1950's, except for the Wonji thermal springs and the Metehara cold spring. The thermal waters in Fantale, Dofan and Meteka have very low tritium values, suggesting that the waters are pre-1950. Geothermometry indicates that the reservoir temperature is in the range 110-140°C (average). The waters do not appear to be completely equilibrated and some mixing with colder water is indicated in all fields. Future studies should give priority to the geothermal prospect of Dofan, followed by Meteka and Fantale.

1. INTRODUCTION

The Ethiopian Rift Valley is part of the Great East African Tertiary-Quaternary Rift System. It extends from the Ethiopian-Kenya border to the Red Sea for over 1000 km within Ethiopia in a north-northeasterly direction. It covers an area of 150,000 km^2. It can be divided into two broad units, the Main Ethiopian Rift and the Afar Rift, which includes the Danakil depression. The rift floor rises to 1230 m a.s.l. at Lake Chamo in the south and decreases to 120 m b.s.l. in the Danakil depression in the north. Tectonic fragmentation of the rift floor formed fault swarms, including the Wonji fault belt (WFB) which is considered to be a recent crustal extension, active since early Quaternary and normal to the rift axis, but ceases where it abuts directly against the rift margin (Mohr, 1967).

So far, the Aluto-Langano geothermal field in the Main Ethiopian Rift Valley, and the Tendaho geothermal field at the junction of the Southern Afar and Northern Afar Rift Valleys have been identified through exploration drilling for electric power generation as high-temperature geothermal fields.

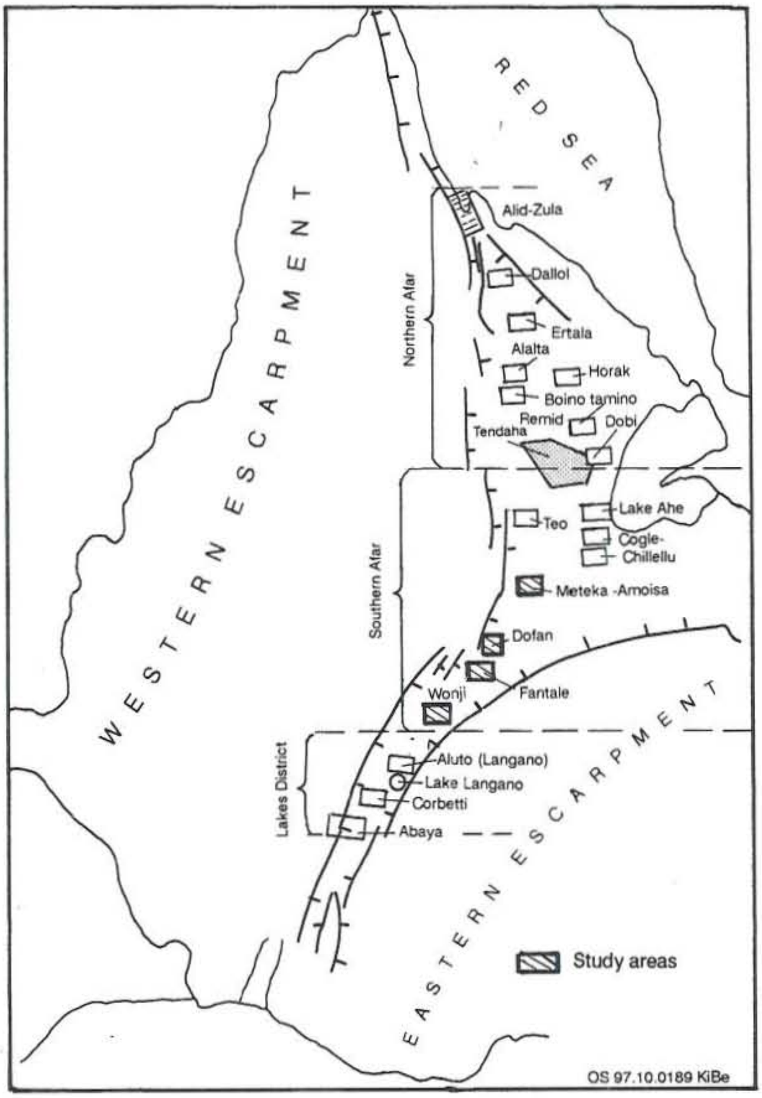

FIGURE 1: Map showing geothermal areas in the Ethiopian Rift Valley

The Southern Afar rift is a part of the Ethiopian Rift Valley system. It is located between 8-12°N and 39-41°E, between the Ethiopian Main Rift in the south and the Northern Ethiopian rift in the north. It covers the area between Wonji and Tendaho (Figure 1).

Geochemical, geological and hydrological studies in the main region of Southern Afar have led to the identification of four potential geothermal prospect areas (Wonji, Fantale, Dofan and Meteka). The studies confirmed the presence of high-temperature geothermal fluids at shallow depth due to magmatic heat sources and further studies were recommended (UNDP, 1973).

During the last 25 years, different geoscientific studies have been carried out in the Ethiopian Rift Valley, in general. Among these, isotopic studies were done for evaluation of geothermal reservoir temperature and the identification of recharge areas for geothermal fields. In most cases, these studies were regional but not detailed. In this study an attempt is made to concentrate on the Southern Afar Rift Valley, using isotopic and chemical data from 1993.

2. PURPOSE AND SCOPE OF STUDY

This study is the result of a six months Fellowship awarded to the author by the International Atomic Energy Agency, based on the technical cooperation agreement project ETH/ 8/004 with the Ethiopian Institute of Geological Surveys, entitled "Isotope investigation of geothermal fluids in the Ethiopian Rift Valley", to study groundwater hydrology at the UNU Geothermal Training Programme.

An isotopic study needs a systematic sampling programme of precipitation, surface waters, cold springs, boreholes, hot springs, geothermal wells and fumaroles for a number of years, in order to understand the hydrological regime and to construct a base map of groundwater systems. In light of this, the present work can be seen as a start in the interpretation of the available isotopic and chemical data, to understand the most common hydrological processes in the studied areas.

During the sampling of 1993, 25 samples were collected, 3 from Asela (1 rain, 1 river, 1 dug well), 7 from Wonji (1 river, 1 borehole, and 4 hot springs), 9 from Fantale (2 rivers, 1 lake, 2 boreholes, 1 cold spring and 2 hot springs), 3 hot springs from Dofan and 3 hot springs from Meteka (Figure 2).

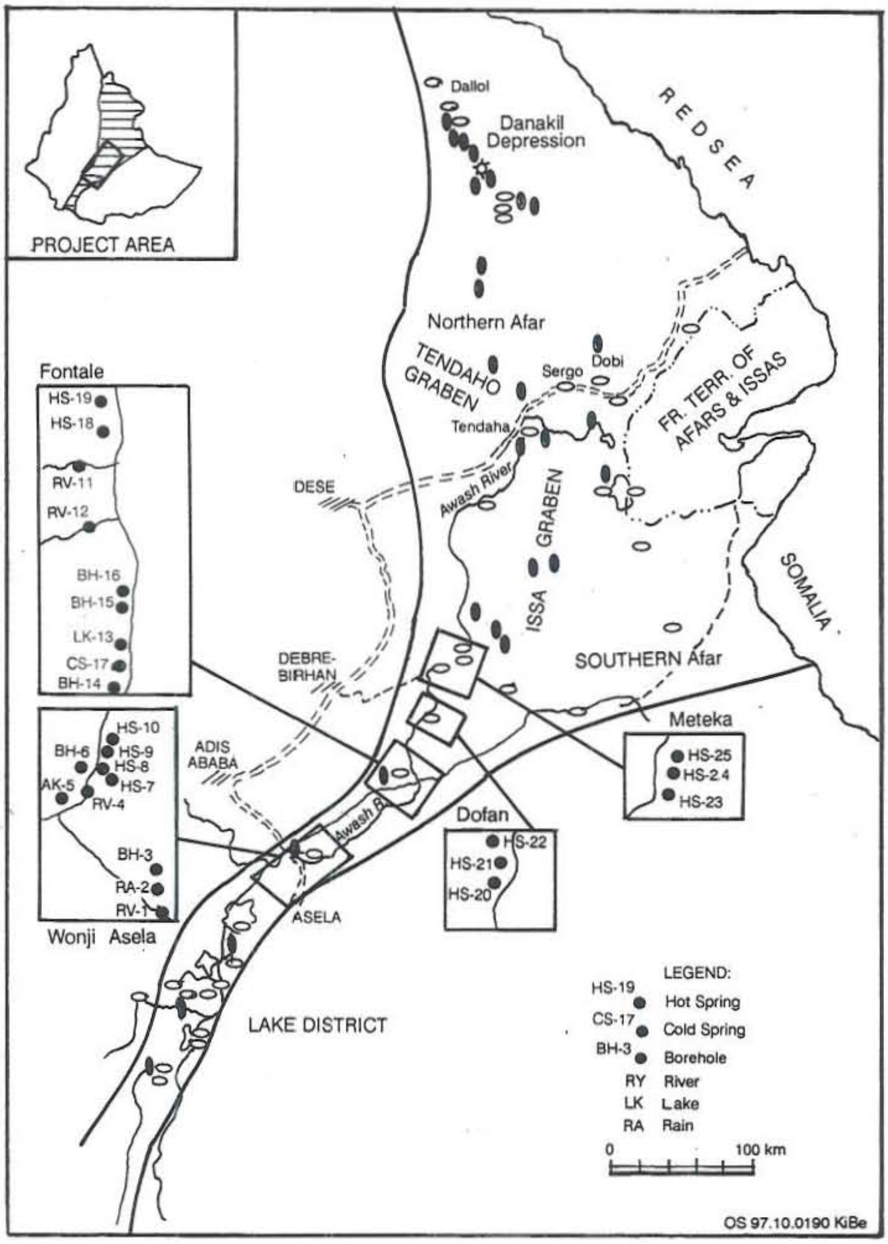

FIGURE 2: Approximate location of sampling sites (not scaled)

3. PREVIOUS WORK

The first isotopic study in the Ethiopian Rift Valley dates back to 1968-1970. During this time, i.e. in 1968-1969 and 1969-1970, two expeditions to the Danakil depression (Northern Afar region) were organised by the Italian C.N.R (Consiglio Nazionale delle Ricerche) in collaboration with the French C.N.R.S (Centre National de la Recherche Scientifique). The geology, petrology and geochemistry of the depression were investigated. Also, water samples for isotopic analyses were collected from two distinct areas, the Dallol thermal spring area and the Giulietti lake region (Gonfiantini et al.,1973).

The objective of the expeditions was to investigate the origin of the water in the two areas and the eventual modification of the original isotopic composition due to isotopic exchange processes and evaporation. From the isotopic study of the Dallol hot springs composition and the lake Giulietti at different depths, the Dallol hot springs were found to be enriched in ^{18}O with respect to the meteoric waterline. This was explained by isotopic exchange reactions between rocks and the circulating geothermal water. The isotopic composition of lake Giuiletti was found to decrease both in $\delta^{18}O$ and δD down from 40 m depth, due to seasonal stratification of the lake.

Later, a regional isotopic study covering almost the whole of the Ethiopian Rift Valley was conducted by Craig (1977). Environmental isotopes of ^{18}O, D, tritium, ^{4}He, ^{14}C and ^{13}C were analysed and interpreted. He confirmed the presence of a high-temperature deep circulating geothermal fluid, useable for electric power generation.

A similar regional isotopic study was done by an Italian state company, Aquater, in 1994. The study mainly focussed on the Tendaho graben and the Western Escarpment, starting from Maichew to Senbetie, to identify the recharge area of the Tendaho geothermal field. It was concluded that the Tendaho geothermal field is not recharged from the area between Maichew and Senbetie and further studies were recommended to the south of Senbetie. Isotopic studies (^{18}O, D, tritium and ^{14}C) of liquid water and gases (CO_2 ,CH_4 and H_2), collected from the Tendaho graben from geothermal wells, hot springs and fumaroles, suggested the existence of a high-temperature geothermal fluid, possibly magmatic in origin, recharging the Tendaho geothermal field.

Panichi (1994) studied all the available isotopic data, starting from 1993, during his mission as an IAEA project expert. The samples were collected by the geochemical staff of the Geothermal Exploration Project, Ethiopian Institute of Geological Surveys (EIGS) and were analysed by the isotope hydrology section of the International Atomic Energy Agency (IAEA), Vienna, Austria, under the cooperation project ETH/8/003, entitled "Isotope investigation of geothermal fluids in the Ethiopian Rift Valley". He interpreted ^{18}O, D, and tritium data from the Ethiopian Rift Valley and suggested the possible existence of regional groundwater, which flows from the Ethiopian Main Rift Valley (Lakes districts) in the south to the northeast through the Southern Afar region, recharging the Tendaho graben.

The last study was done by Teclu (1995) during his training in isotope hydrology at the International Atomic Energy Agency, Vienna, Austria. He used the stable isotopic and chemical data of samples collected from the Western Escarpment and the Southern Afar region in 1995 to trace the origin of the geothermal fluid feeding the Tendaho geothermal field. In the study, the weighted mean precipitation for Addis Ababa (IAEA monthly rain collections (1961-70)) was used for comparison of groundwater isotopic data to local meteoric water. Teclu´s interpretations (Teclu,1995) were in agreement with earlier work (Panichi,1994) where regional groundwater flow was suggested from the southern part of the Ethiopian Rift Valley to the Tendaho graben. Teclu (1995) recommended an interdisciplinary study of the geology, geochemistry, hydrology and meteorology to assess the recharge mechanism and regional groundwater movement in the area.

4. GEOLOGICAL SETTING

The Afar rift is located northeast (9°N, 40°E) of the Main Ethiopian Rift. This triangular region is bounded to the southeast by the Somalia plateau and to the northeast by the Red Sea. The Western Escarpment is about 3000 m a.s.l. at Tarmaber pass near Deberesina. Faults of the Main Ethiopian Rift Valley (trending north-northeast), Gulf of Aden (trending east) and the Red Sea (trending northwest) penetrate the Afar region. Surface faulting of the Main Ethiopian Rift Valley can be traced as far northeast as Tendaho, but becomes indistinct north of 10°N. From both geological and geophysical evidence it appears probable that a narrow spreading zone of the Red Sea direction intersects Afar, where the silicic crust is absent or thin. Therefore, assimilation and or anatexis is a likely origin for at least the silicic rocks in Afar. This implies that a magma chamber exists within the crust and, together with anomalously high heat flow direct from the upper mantle, is believed to be the source of heat for the hot springs and fumaroles in the Ethiopian Rift Valley, in general, and in Afar region in particular (UNDP, 1973). Much of the basalts of Central and Southern Afar erupted to the surface through narrow fissures penetrating the comparatively thick crust. A majority of the fields are associated with grabens in which thick Quaternary lavas, tuffs and sediments of marine, lacustrine and terrestrial origin have accumulated. In general, the geologic environment is encouraging for the location of geothermal energy resources (UNDP, 1973).

5. THEORETICAL BACKGROUND - ^{18}O, D AND TRITIUM ISOTOPES

The stable isotopes of δD and $\delta^{18}O$ in natural waters have been studied by Craig et al. (1956). Table 1 shows the results for oceanic waters.

TABLE 1: Relative abundance of stable isotopes in oceanic waters (Craig et al., 1956)

Component	Relative abundance	Mass	Vapour pressure at 30°C (mmHg)	Vapour pressure at 100°C (mmHg)
H_2O	1	18	31.5	760
HDO	1/3230	19	29.4	241
H_2O^{18}	1/500	20	31.3	756

When natural water evaporates in a system where thermodynamic equilibrium is maintained, the concentration of the components in the vapour and liquid phases is controlled by the respective vapour pressure. The isotopic relationship can be studied on the basis of the Rayleigh distillation model. In this model, the vapour is depleted in the heavier isotopes and the condensate is enriched.

Experimental studies have shown that the isotopic relationship in meteoric water is governed by the natural water cycle of evaporation - condensation under equilibrium conditions. The oceanic precipitation is progressively depleted in the heavy isotopes as a function of the distance of precipitation from the local atmospheric reservoir. Two facts can be seen. First, there will be an approximately constant ratio of $\Delta D/\Delta^{18}O$ where Δ indicates depletion relative to a given standard. Therefore, water derived from the meteorological cycle has a natural label and can be distinguished from any water derived from a source with a different isotopic relationship. This may provide a method of detecting juvenile components. Secondly, there is a general decrease in the heavy isotopic concentration as the latitude varies from the equatorial to the polar. This reflects a continuous loss of vapour from the air masses moving poleward. Consequently, precipitation has a latitude effect or a latitude label. It must, however, be emphasized that the latitude effect is often complex and dependent on local meteorological conditions, hence, there are substantial time variations in the heavy isotopic concentrations of the local precipitation.

The radioactive isotope, tritium, with a half life of 12.5 years, decays to ^3He. Its concentration is very low in natural waters. The average rain water, prior to the hydrogen bomb testing in the 1950's, has T/H of $5*10^{-18}$ (1 T.U is equivalent to a T/H of $1*10^{-18}$). Natural water derives tritium from the atmosphere, where it is believed to be produced at high altitudes by the action of cosmic radiation. Tritium is not produced in surface water or groundwater. Therefore, its concentration in groundwater will decrease as a result of radioactive decay. In principle, it should be possible to use the tritium concentration of groundwater to determine the age of the water, that is to say, since it left the atmosphere. The difficulty is that tritium can be produced in nuclear reactors which, hence, contaminates natural tritium.

5.1 Stable isotopes ^{18}O and D

The fact that the precipitation is labelled by its isotopic concentration suggests an application along two lines. First, the ratio $\Delta D/\Delta^{18}O$ in thermal water indicates any admixtures with components that are not derived from oceanic - meteorological systems. Secondly, as thermal and groundwater, in general, may percolate a long distance underground, their isotopic concentration may differ from the that of the local precipitation at the spring. Hence, a systematic study of the precipitation in the region may lead to the detection of a recharge area. This method is applicable both in groundwater hydrology and geothermal work.

During the exploitation of natural heat resources by drilling, there is a danger of infiltration of cold groundwater surrounding the thermal area. The cold water encroaches on the thermal water and appears in wells after a certain time lag. In this case the isotopic concentration of the cold water differs from that of the thermal water. Therefore, the first changes to be observed in the wells are changes of the isotopic concentration. Temperature changes will occur later, due to an exchange of heat between cold water and hot water. Thus, the isotopic concentration in the thermal water may be an important indicator of unwanted or dangerous changes in the flow pattern in the heat reservoir.

5.2 Tritium

The tritium concentration in precipitation has risen by certain orders of magnitude as a result of nuclear tests between 1950-1960. A substantial part of the tritium from each test, partially stored in the stratosphere, will leak for a period of years into the lower layers. The changes in the tritium concentrations of springs are in most cases slow; a single sample from a spring represents tritium concentration of that spring for a period of many months or often a longer period.

Large variations in groundwater recharge will be reflected in the tritium concentration of the spring. The tritium in spring water depends on the tritium concentration of precipitation in a complicated manner. The springs can, for example, either be composed of different waters of various age or come from a large well mixed reservoir of waters of different age.

Tritium measurements can be very useful, even though they give no conclusive age of the groundwater. Certain information about the mean age can often be obtained, and the measurements of tritium can often show that two adjacent springs are fed by different groundwater systems. Mostly tritium results are used for comparative age determination of groundwater systems, such as springs, boreholes and wells rather than absolute age determination of groundwater systems.

6. METHODS OF SAMPLING AND ANALYSIS

6.1 Field sampling procedures

Collection of water samples from rain, rivers, lakes, dug wells, boreholes, cold springs and hot springs for isotope and chemical analyses were conducted during 1993 in the Southern Afar region, Ethiopian Rift Valley. The areas of Asela, Wonji, Fantale, Dofan and Meteka (Figure 1) were covered by this sampling programme. Water samples were collected using double capped polyethylene bottles and the sampling methods are shown in Table 2.

All hot springs were collected from relatively strong flows and high temperatures. The flows are assumed to remain almost constant throughout the year. River and lake samples were taken by deepening sampling vessels to an approximate depth of 30 cm. Dug wells and boreholes were sampled from the water level using a tied bucket with nylon rope. The precipitation sample from Asela was collected from the nearby meteorological station. Sampling points are identified by their locality name and feature type. When there is a similar feature type in the same area, a number is given for further identification (Figure 2). Appendix 1 lists sampling details and correlates locations with sampling numbers.

TABLE 2: Sampling methods in the field

No.	Size of bottle (ml)	Type of analysis	Treatment
1	50	δ^{18} and δD	Untreated
2	50	Silica	Diluted down to 100 ppm with distilled water, if silica concentration is greater than 100 ppm
3	100	Major cations	Filtered and acidified with 1 ml of (1+1) conc. HCl
4	100	Cl and SO_4	Filtered and 1 ml of 1M zinc acetate is added
5	500	Major anions including boron	Untreated
6	500	Tritium	Untreated

6.2 Field measurements and chemical analysis

Temperature. A maximum thermometer was used to measure the temperature in degree centigrade of the hot springs directly from the point of maximum flow.

pH. The pH of the samples were measured using a calomeal glass electrode (ORION TYPE) at the sampling temperature.

Silica was determined using the visual calorimetry method based on the principle of ammonium molybdate reagent for the formation of the blue colour complex with silica.

Total carbonate was determined by titrating 0.2 ml of the sample with 0.1 N HCl or with 0.01 N HCl, depending on the concentration of total carbonate in the sample, to methyl orange end point, about pH of 3.8, using a micro alkali metre.

6.3 Laboratory analysis

Isotope and chemical analysis were carried out by the Isotope Hydrology Laboratory of IAEA, Vienna, Austria. Also, duplicate water samples collected for all samples were analysed by the Central Geological Laboratory of EIGS, Addis Ababa, Ethiopia. In this work, the chemical interpretation is based on analytical results of the Isotope Hydrology Laboratory of IAEA. The following laboratory analytical methods were used:

Element analysed	Method of analysis
Ca	Atomic absorption spectrophotometry
Mg	Atomic absorption spectrophotometry
Na	Atomic absorption spectrophotometry
K	Atomic absorption spectrophotometry

CO_3	Alkalimetry- titration
HCO_3	Alkalimetry- titration
Cl	Ion chromatography
SO_4	Ion chromatography
NO_3	Spectrophotometry
SIO2	Spectrophotometry
F	Ion selective electrode
pH	Ion selective electrode
^{18}O	Mass spectrophotometry
D	Mass spectrophotometry
^3T	Mass spectrophotometry

Conductivity was measured using a conductivity meter

7. ANALYTICAL RESULTS

The samples were analysed by the Isotope Hydrology Laboratory of the International Atomic Energy Agency and results are given in mg/kg for major cations and anions (Tables 3 and 4).

TABLE 3: Analytical results of major constituents for Asela, Wonji and Fantale areas, concentrations in mg/kg and conductivity in µs

Feature	Cond.	pH	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	F	SIO_2
ASELA													
Kulumsa, river		6.9	4.0	1.2	2.7	1.3	0.0	29.4	1.7	1.5	0.0	0.0	18.4
Kulumsa, rain	24.8	6.6	1.4	0.1	0.3	0.3	0.0	12.4	0.7	2.2	3.0	0.0	0.4
Wonji G.D.W.	48.5	7.3	17.4	1.7	24.7	9.2	0.0	112.6	5.6	13.4	7.6	0.6	85.6
WONJI													
Awash river	230.6	7.5	18.9	3.4	23.2	4.1	0.0	128.1	7.2	4.7	0.0	1.4	22.1
Koka lake	187.2	7.2	19.4	4.0	11.9	3.4	0.0	103.5	7.0	3.7	0.0	0.7	24.5
Nazret W. Sup.	881.6	8.3	52.3	9.4	136.4	23.7	0.0	511.7	29.3	15.7	12.1	4.4	88.6
Hipoo pool 1	939.8	8.1	2.9	0.7	229.3	14.5	0.0	493.0	23.5	30.8	3.6	16.9	104.0
Hipoo pool 2	919.1	8.0	2.8	0.7	223.7	14.1	0.0	496.0	24.9	25.2	0.0	15.4	103.1
Hipoo pool 3	908.0	8.0	2.3	0.7	221.6	14.0	0.0	496.6	25.7	23.1	0.0	14.8	102.8
Hipoo pool 4	993.6	8.4	3.4	0.8	238.6	16.0	8.6	515.6	27.5	26.8	0.0	18.1	110.6
FANTALE													
Kebena river	173.4	7.3	21.3	5.4	6.7	1.6	0.0	107.3	2.6	2.5	0.4	0.3	27.8
Bulga river	215.0	7.4	30.4	4.9	7.6	2.4	0.0	132.1	3.4	2.8	0.0	0.7	24.5
Metehara lake	1377.0	9.6	1.7	0.3	2032.0	66.7	698.2	2156.0	578.7	495.6	0.0	3.7	109.4
Welin. W.Sup.	651.7	8.3	16.8	10.1	122.3	13.6	3.0	404.7	8.1	9.3	5.4	0.8	100.6
Mete.T. W.Sup.	1555.0	8.4	43.0	9.6	338.6	7.5	14.8	900.5	54.7	54.0	0.0	11.2	77.1
Mete.Msq.D.W.	4668.0	9.0	1.3	0.2	1176.1	42.8	137.1	1546.0	367.8	407.0	203.0	7.7	51.2
Mete.cold sp.	1345.0	7.7	113.2	15.9	153.4	7.9	0.0	113.2	49.0	320.7	234.6	1.8	47.0
Fantale hot sp. 1	1891.0	8.2	1.5	1.2	456.2	21.8	0.0	806.8	178.6	89.3	0.0	7.6	64.4
Fantale hot sp. 2	1752.0	8.5	2.0	2.2	422.7	20.9	14.4	734.2	146.1	84.0	1.5	5.9	64.1

TABLE 4: Analytical results of major constituents for Dofan and Meteka hot springs, concentration in mg/kg and conductivity in µs

Feature	Cond.	PH	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	F	SIO_2
DOFAN													
Hot spring 1	1556.0	8.2	3.2	0.1	357.2	16.7	0.0	427.1	172.6	168.1	0.7	7.88	124.5
Hot spring 2	1555.0	8.4	3.8	1.0	347.6	17.5	5.6	420.6	171.8	164.8	0.8	7.59	122.6
Hot spring 3	1754.0	8.3	8.8	0.7	395.0	15.6	0.0	401.1	204.6	216.4	8.2	13.8	112.6
METEKA													
Hot spring 1	1173.0	8.2	3.6	1.9	265.2	11.4	0.0	408.5	119.7	92.4	1.4	1.8	62.4
Hot spring 2	1198.0	8.4	3.7	1.9	274.0	11.4	4.4	398.4	123.2	94.3	2.1	1.88	61.2
Hot spring 3	1312.0	8.2	3.5	1.7	300.7	11.6	0.0	428.5	144.0	105.6	0.9	1.94	59.9

Isotopic results of isotope analysis are reported in delta notation, i.e deviation from the Vienna Standard Mean Oceanic Water (VSMOW) with uncertainty levels of ±0.1‰ and ±1.0‰ for $\delta^{18}O$ and δD, respectively (Table 5).

TABLE 5: Results of isotope analysis and deuterium excess values

Area	Feature	$\delta^{18}O$	δD	TU	σ TU	d-excess
Asela	Kulumsa,.river	-2.0	0.1	6.4	0.4	16.3
	Kulumsa, rain	-0.3	11.9	6.1	0.5	14.0
	Wonji G.D.W.	-1.5	-0.4	5.7	0.4	11.3
Wonji	Awash river	-0.2	4.9	7.8	0.4	6.7
	Koka lake	-0.4	6.3	8.2	0.5	9.1
	Nazret W. Sup.	-2.0	-5.6	6.9	0.4	10.6
	Hipoo pool 1	-1.7	-1.6	18.8	0.8	12.1
	Hipoo pool 2	-1.6	-3.0	17.1	0.7	10.0
	Hipoo pool 3	-1.6	6.7	16.2	0.7	19.6
	Hipoo pool 4	-2.1	-7.4	21.1	0.9	9.0
Fantale	Kebena river	-2.0	2.4	7.5	0.4	18.4
	Bulga river	-0.6	9.4	6.7	0.4	14.3
	Metehara lake	7.3	43.4	3.9	0.3	-15.2
	Welin. W.Sup.	-4.4	-21.1	0.5	0.1	14.1
	Mete.T. W.Sup.	-0.4	3.3	6.5	0.4	6.1
	Mete.Msq.D.W.	-1.1	-4.8	2.2	0.3	4.3
	Mete.cold sp.	0.6	21.5	15.7	0.2	16.5
	Fantale hot sp. 1	-2.8	-14.1	0.3	0.3	8.5
	Fantale hot sp. 2	-2.9	-15.4	0.3	0.3	7.4
	Metehara rain†	-2.7	-9.9	na	na	11.9
Dofan	Hot spring 1	-1.3	-9.4	0.6	0.3	1.1
	Hot spring 2	-1.2	-7.1	0.5	0.3	2.5
	Hot spring 3	-1.6	-8.6	0.5	0.3	4.3
Meteka	Hot spring 1		-16.3	-0.1	0.3	6.1
	Hot spring 2	-2.8	-9.5	0.1	0.3	13.1
	Hot spring 3	-2.7	-13.8	-0.1	0.2	7.6

† Metehara rain sample from 1995 isotope analysis data; na = not analysed.

The following formula was used for reporting δ-values in per mille:

$$\delta sample = ((R_{sample} - R_{standard})/R_{standard}) * 1000 \qquad (1)$$

where

R_{sample} is the isotopic ratio of ^{18}O / ^{16}O or D /H
$R_{standard}$ is the same isotopic ratio measured for the Vienna Oceanic Water Standard.

The following general relationship between δD and $\delta^{18}O$ has been established for meteoric water worldwide (Craig, 1961a):

$$\delta D = 8\delta^{18}O + 10 \qquad (2)$$

Deuterium excess is defined from the meteoric waterline as

$$d = \delta D - 8\delta^{18}O \qquad (3)$$

Deuterium excess is mainly dependent on the sea surface temperature in the source area of the water vapour. It has been used to evaluate the origin of precipitation (Johnsen et al., 1989).

8. DISCUSSION

8.1 Methods for chemical and isotopic interpretation

Classification of the geothermal waters was done by using major anions and cations using the well known Piper diagram. Triangular plots of the three main anions, Cl, SO_4 and HCO_3, are commonly used for classification of the water types and for choosing geothermometers. In a geothermal chemistry study, the knowledge of sub-surface temperature is of major importance. The depth of the heat source, the type of rock, the permeability of the reservoir, the type of cap rock and tectonic structures of the geothermal field are the most important parameters affecting the chemical and isotopic composition of fluid discharged at the surface. Fluids can have different chemical characteristics depending on their origin and history of flow from a reservoir to the surface, and will plot near one of the three corners of the Cl, SO_4 and HCO_3 drawing. Acid waters plot to the corner of the sulfate ion and are not suitable for use as geothermometers. Alkali chloride waters that plot near the chloride corner are most suitable for the majority of geothermometers. Figure 3 shows a Cl-SO_4-HCO_3 diagram, in which the results of the present study have been plotted. It can be seen that almost all geothermal waters are HCO_3 type waters; only geothermal waters from Dofan plot around a point of 50% HCO_3, 25% Cl and 25% SO_4.

Table 6 shows the ratio of main cations to chloride. It shows a rather stable and significant value within each field. The same relationship was found for the Na-K ratios. The study of conservative elements, i.e. those elements which are very soluble and stay in solution without taking part in water-rock interaction, aids in evaluating the origin and possible flowpath of the groundwater system, as well as marking processes such as dilution and evaporation. Therefore, ratios between conservative elements like B/Cl, Br/Cl and Li/ Cl should be similar for waters with a common origin.

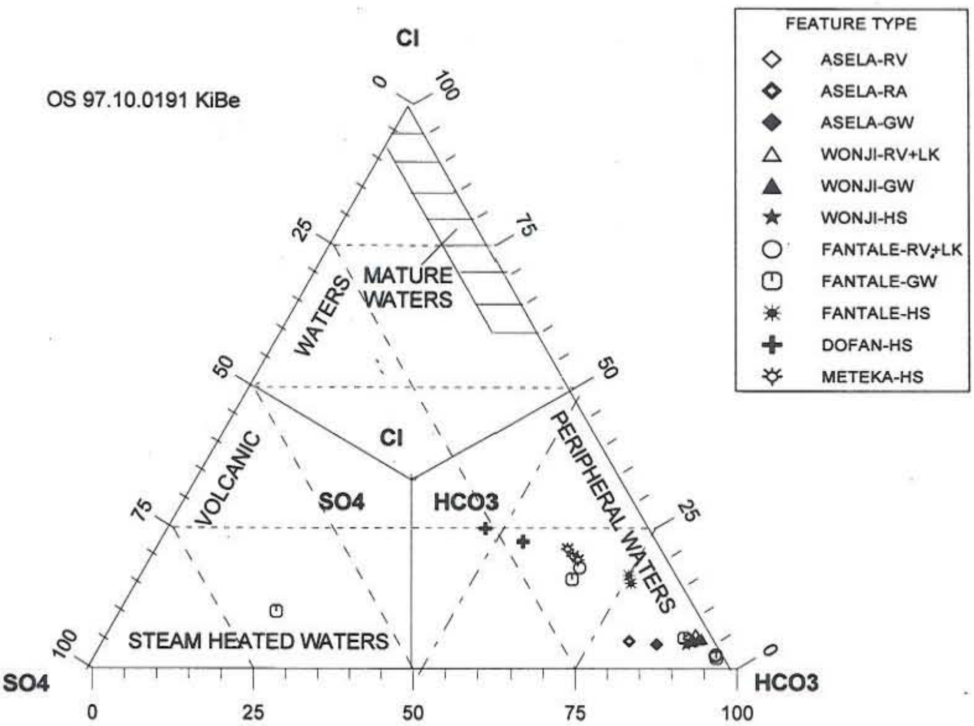

FIGURE 3: A Cl-SO_4-HCO_3 diagram for the Southern Afar waters

TABLE 6: Some useful ratios of the Southern Afar hot springs for interpretation of water chemistry

Area	Feature	Na-K	Ca/Cl	Mg/Cl	Na/Cl	K/Cl
Wonji	Hipoo pool 1	15.79	0.13	0.03	9.77	0.62
	Hipoo pool 2	15.83	0.11	0.03	8.98	0.57
	Hipoo pool 3	15.82	0.09	0.03	8.64	0.55
	Hipoo pool 4	14.89	0.12	0.03	8.69	0.58
Fantale	Hot spring 1	20.91	0.01	0.01	2.55	0.12
	Hot spring 2	20.18	0.01	0.01	2.89	0.14
Dofan	Hot spring 1	21.34	0.02	0.00	2.07	0.10
	Hot spring 2	19.84	0.02	0.01	2.02	0.10
	Hot spring 3	25.34	0.04	0.00	1.93	0.08
Meteka	Hot spring 1	23.37	0.03	0.02	2.22	0.09
	Hot spring 2	23.97	0.03	0.02	2.22	0.09
	Hot spring 3	25.88	0.02	0.01	2.09	0.08

Isotopic ratios, especially D/H, usually reported as δD, tend to be very conservative and good indicators of the origin of flow, mixing and evaporation (Craig, 1961b). The $^{18}O/^{16}O$ ratio, or $\delta^{18}O$, is similarly useful except that oxygen isotopes are exchanged between hot rock and the circulating meteoric water to produce an "oxygen isotope shift", most usually to higher ^{18}O content in the water, and a reverse shift to lower ^{18}O content of the rock. The extent of the oxygen isotope shift depends on the interaction temperature, water-rock ratio, interaction time and permeability of the rock. Generally, low temperature, high water-rock ratio (i.e high permeability) and low interaction time result in a low oxygen isotope shift.

Precipitation tends to decrease in δD and $\delta^{18}O$ with increasing latitude, altitude, and inland distance from the sea. The same effect is seen with decreasing temperature. The isotopic composition also depends on the amount of precipitation and on many other meteorological conditions. For this reason it is essential to first determine the local meteoric water line of a certain area using the weighted mean results of long term collection of precipitation samples for δD and $\delta^{18}O$ analysis.

The weighted mean precipitation of Addis Ababa, the capital city of Ethiopia, was used to construct the local meteoric water line by Teclu (1995). That line is used for this study and is given as follows:

$$\delta D \;=\; 8^{18}O + 12.5\,AAMWL \qquad (4)$$

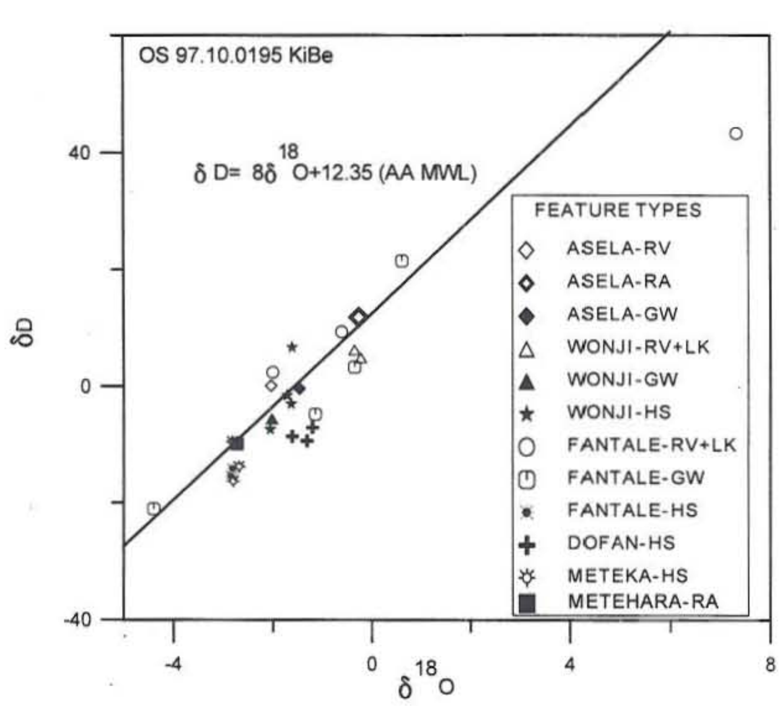

FIGURE 4: A δD vs. $\delta^{18}O$ plot for all the collected samples

In Figure 4 isotopic composition of all the samples used for this study is compared to the line defined by Equation 4. Almost all the samples plot close to the line, except the sample from lake Metehara which shows considerable oxygen isotope shift. As there is not enough isotopic data available, only a general conclusion can be drawn regarding origin and flow pattern of groundwater systems.

Chemical geothermometers of chalcedony and quartz and Na-K have been used to estimate the reservoir temperature of the geothermal waters (Table 7). For the calculation of the saturation index (log (Q/K)), speciation and other thermodynamic computations, the speciation program Watch (Arnórsson et al., 1982; Bjarnason, 1994) has been used. An arbitrary concentration of aluminium, of 0.012 mg/kg, was used for running the Watch program based on concentration in similar water types from Uganda (Ármannsson, 1994).

8.2 Wonji

The Wonji area is located in the Southern Afar Rift Valley, at the boundary of the Lakes District and the Southern Afar Rift Valleys. The area is mainly characterized by north-northeast trending fault swarms, in addition to the Wonji Fault Belt (WFB) thought to be active since early Quaternary (Mohr, 1967).

Seven samples in total, i.e. Awash river (1), Koka hydro electric dam (1), Nazret town water supply borehole (1), and 4 Hipoo pool hot springs (1 from each) were collected during the 1993 sampling programme and analysed for their isotope and chemical constituents. Analytical results are shown in Table 3.

TABLE 7: Results of selected solute geothermometer calculations using measured concentrations of Southern Afar hot springs

Area	Feature	CH	CHs	QRZ	QRZs	Na-K1	Na-K2	Na-K3
Wonji	Hipoo pool 1	113±10	111±10	139±10	135±10	153±10	142±10	198±10
	Hipoo pool 2	112±10	110±10	139±10	134±10	152±10	142±10	198±10
	Hipoo pool 3	112±10	110±10	139±10	134±10	152±10	142±10	198±10
	Hipoo pool 4	117±10	114±10	143±10	138±10	158±10	148±10	202±10
Fantale	Hot spring 1	85±10	88±10	114±10	113±10	130±10	119±10	180±10
	Hot spring 2	85±10	88±10	114±10	113±10	133±10	122±10	182±10
Dofan	Hot spring 1	125±10	120±10	150±10	143±10	129±10	118±10	178±10
	Hot spring 2	124±10	119±10	149±10	143±10	134±10	123±10	183±10
	Hot spring 3	118±10	115±10	144±10	138±10	116±10	105±10	168±10
Meteka	Hot spring 1	83±10	86±10	112±10	112±10	122±10	111±10	173±10
	Hot spring 2	82±10	86±10	111±10	111±10	120±10	109±10	171±10
	Hot spring 3	81±10	85±10	110±10	110±10	115±10	103±10	166±10

CH = Chalcedony no steam loss (Fournier, 1977);
CHs = Chalcedony maximum steam loss (Arnórsson et al., 1983a);
QRZ = Quartz no steam loss (Fournier, 1973);
QRZs = Quartz maximum steam loss (Fournier, 1977);
Na-K1 = (Arnórsson et al., 1983b);
Na-K2 = (Truesdell, 1976);
Na-K3 = (Giggenbach,1980)

The analytical results are plotted on the Cl-SO_4-HCO_3 diagram shown in Figure 3. The diagram shows that all points plot very close to the bicarbonate corner, showing that all the samples are bicarbonate type waters. This is also supported by the alkaline nature of the waters, average pH is about 7.9 and the very low chloride content, ranging from 7.02 mg/kg for Koka electric power dam to 29.32 mg/kg for Nazret town water supply borehole. The chloride content of the hot springs is in the range of 23.5 mg/kg to 27.45 mg/kg. The hot springs probably discharge mostly waters of meteoric origin. The heat source is either a regional high positive heat anomaly or/and shallow magma intrusions which are the main heat source in the Ethiopian Rift Valley (UNDP, 1973).

Comparison of the chemistry of the hot springs and the Nazret town water supply borehole cannot alone give an idea of the amount of geothermal water component, if any, mixing with the local cold meteoric water. The mixing model of silica-enthalpy, shown in Figure 5, was used to detect a possible mixing trend. Since the points plot very close to the origin, it is very difficult to define a mixing line. The chloride content of cold water from the Nazret borehole is slightly higher than the chloride content of the Hipoo pool hot springs. At this stage it is difficult to state anything about the evolution of the hot springs except that they are discharging heated ground waters.

A Na-K-Mg triangular plot (Arnórsson, 1991) is used to see whether there is equilibrium of the hot springs at depth. Results are shown in Figure 6. As seen from the diagram, samples of the hot springs plot at the same point near the boundary line between immature waters and partially equilibrated waters and are in the region of partially equilibrated waters. Based on this plot, the reservoir temperature at depth might be between 140 and 160°C.

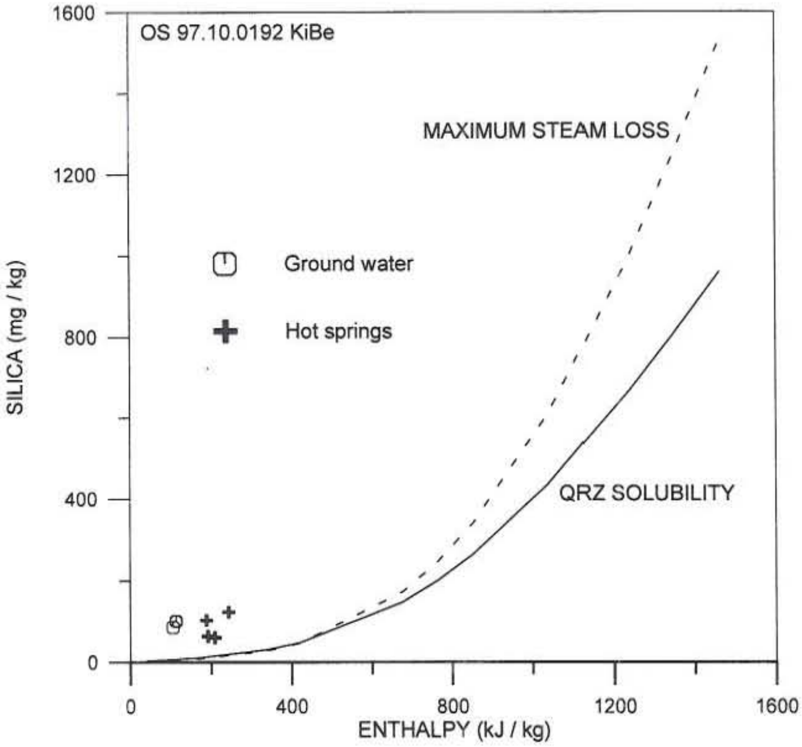

FIGURE 5: A silica vs. enthalpy diagram for the Wonji waters

Since the chemistry of all the hot springs is very similar, and the atomic ratios of some selected elements are approximately the same (Table 6), the analytical data of Hipoo pool 4 which has the highest spring temperature was chosen for construction of saturation index log Q/K vs. T(°C), (Figure 7). As shown in the figure, a few curves for the minerals considered intersect the zero line at temperatures between 70 and 95°C, but do not converge at a unique point. Curves for a few other minerals intersect at log Q/K < 0, at about 140 and 160°C. The log Q/K diagram suggests that there is some mixing of hot water with lower temperature waters. A similar result for the Katwe-Kikorongo hot springs, Uganda, (Ármannsson, 1994) was found

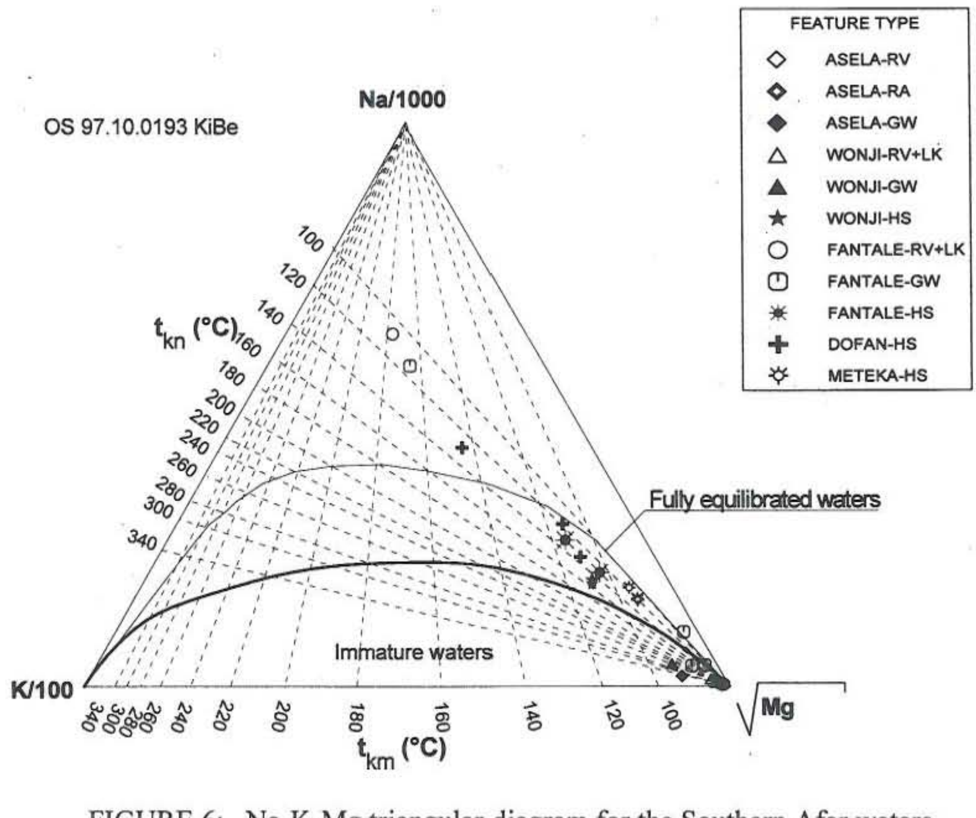

FIGURE 6: Na-K-Mg triangular diagram for the Southern Afar waters

for the minerals calcite, albite and adularia, considered in both studies. In the case of the Katwe - Kikorongo hot springs, most of the minerals considered intersect the zero line at 80-120°C, but do not still converge sharply at a unique point. A few other curves intersect at log Q/K < 0 at approximately 150°C.

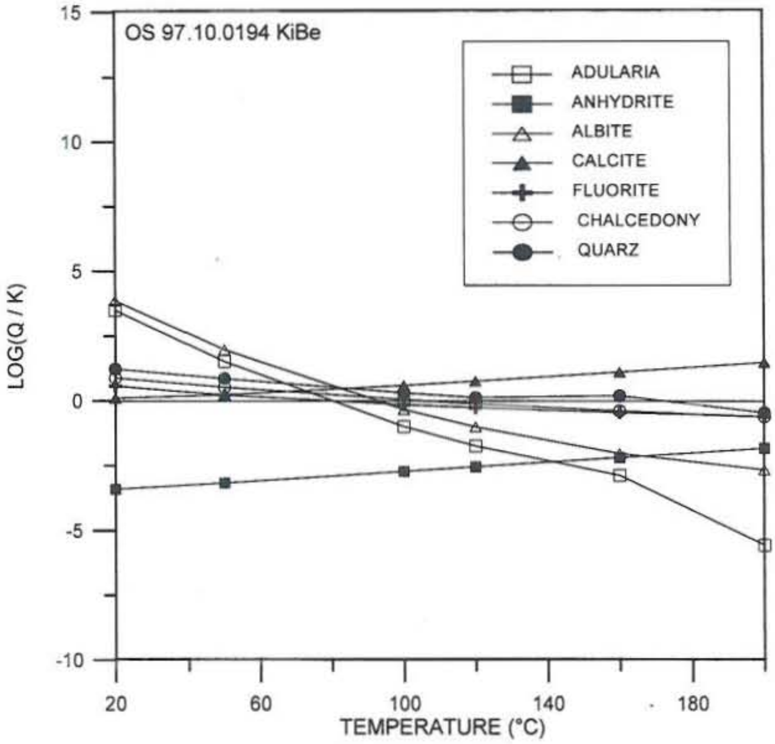

FIGURE 7: Log Q/K vs. temperature for the Hipoo pool 4 data

Temperatures estimated using selected geothermometers are tabulated in Table 7. The temperatures estimated by each type of geothermometer gave approximately the same result for all Hipoo pool hot springs. The lowest temperature, about 113°C (average), is estimated by a chalcedony silica geothermometer (Fournier, 1977) and the highest temperature, approximately 199°C (average), is estimated by the Na-K geothermometer (Giggenbach, 1980). Other calculated values fall between the two. Concerning the type of underground rocks, one might expect that the quartz geothermometer might be the most appropriate of the silica geothermometers. The deeper temperature obtained by the quartz geothermometer compares rather well with the values obtained from Na-K geothermometers by Arnórsson et al. (1983b) and Truesdell (1976), indicating a reservoir temperature of 134-143°C for the samples considered. There is probably some mixing with cold water as discussed above; therefore a deep temperature of minimum 150°C might be expected.

All isotopic data, including samples from the Wonji area, are shown in Figure 4, using Addis Ababa Meteoric Water line (AAMWL) for comparison as a local meteoric water line. This is done due to lack of isotopic data of cold springs and precipitation from the area. However, since the AAMWL is approximately similar to the world meteoric waterline, the difference with the Southern Afar region is not thought to be significant. It can be seen from the figure that the Hipoo pool hot springs are very similar in $\delta^{18}O$ (-2.0‰), whereas considerable range is observed in their δD composition (-7.4‰ to +6.7‰). Furthermore, Figure 4 shows that the Nazret town water supply, representing the groundwater of the area, is similar in $\delta^{18}O$ to the hot springs and lies close to the AAMWL line. The surface waters, i.e the Awash river and Koka hydro electric power dam, have similar isotopic composition (-0.3‰ in $\delta^{18}O$ and +5.5‰ in δD) and plot slightly below the local meteoric waterline, indicating slight evaporation.

A sample of precipitation from a meteorological station and a groundwater sample from a hand dug well were collected for isotopic analyses from the Asela region, located in the Eastern Escarpment (Figure 1), in order to evaluate if this region is a possible recharge area for the Southern Afar geothermal fields. This data is also shown in Figure 4. The figure demonstrates that the oxygen isotopic composition of the sample from the Wonjigora dug well in the Asela highland is similar to that of the hot and cold groundwater in the Wonji area, suggesting some groundwater connection between the regions. It is however, striking that the tritium concentration is similar for the cold groundwater in Asela and Wonji (modern values), whereas it is considerably higher for the Wonji hot waters (Table 5). The high tritium content of the hot springs suggests that the springs contain a component of water from the hydrogen bomb tests and is, therefore, older than the cold groundwater of Asela and Wonji.

The three hot springs Hipoo pool 1, 2, and 4 have d-excess of 12.08‰, 10.04‰ and 9.00‰, respectively. Exceptionally, Hipoo pool-3 has a much higher deuterium excess, about 19.58‰. The three hot springs can be treated as a groundwater system similar to that of the Wonjigora and the Nazret cold groundwater. With the available data it is difficult to explain the high δD values for Hipoo pool 3. It has similar chemical composition, as regards major cations and anions to that of the other three hot springs. The hot springs are located very close to each other near the Awash river. Due to the similarities, it is difficult to assign different aquifer systems based on the deuterium content alone, as the other isotopic differences are minor and can be accounted for by analytical error. Based on this information, the hot springs probably emerge from the same aquifer system.

The two surface samples from Awash river and Koka hydro-electrical power dam have heavier δD and $\delta^{18}O$ values than the other samples from the area, and slightly below the local meteoric waterline, suggesting slight evaporation. If the source of these waters is suggested to be the same as for cold groundwater in the Wonji area, the model of Sveinbjörnsdóttir and Johnsen (1989) suggests that the line of evaporation has a slope of about 5.7 and an evaporation ratio of about 5%.

8.3 Fantale

The Fantale area is located in the Southern Afar region, northeast of Wonji. The general geology is as presented in Chapter 4. It is very similar to the geology of the Wonji area. Samples from 2 rivers, 1 lake, 1 dug well, 2 boreholes, 1 cold spring and 2 hot springs were collected during the 1993 sampling programme. In total, nine samples were collected. Analytical results are tabulated in Table 3.

The analytical results representing the area are used for plotting different diagrams. Data of Cl-SO_4-HCO_3 are plotted in Figure 3. Most of the data points plot in the region of HCO_3, except the cold spring, which plots near the SO_4 corner. Hence these waters are not pure bicarbonate waters as those of the Wonji area. They have higher chloride content than the Wonji waters, even much higher in the samples from Metehara lake and Metehara mosque dug well, 578.7 mg/kg and 367.8 mg/kg, respectively. The hot springs, Fantale-1 and Fantale-2 have a chloride content of 178.6 mg/kg and 146.1 mg/kg, respectively. Therefore, the waters are bicarbonate type with a little mixture of chloride and sulphate.

Comparison of the chemistry of the different types of samples may group the samples based on similarity of chemical compositions for the major cations and anions. Three distinct chemical groups can be observed, 1) rivers, 2) Metehara lake and Metehara mosque dug well, and 3) the hot springs. The remaining three are not chemically similar to any of the groups. To track the origin of these waters, the silica-enthalpy mixing model has been used to find any mixing processes, if any. Similar to that of the Wonji area waters, the data points plot very close to the origin (Figure 5).

The results of the Na-K-Mg triangular plot are shown in Figure 6. The diagram shows that the samples from the hot springs plot in the region of partially equilibrated waters. Even though the waters are not fully equilibrated, they seem to be moving to the fully equilibrated waterline. A temperature of 100-120°C is indicated by the data points. If these waters follow the same trend and are fully equilibrated, the equilibration temperature will most likely be in the range 120-140°C, which is lower than for the Wonji thermal water.

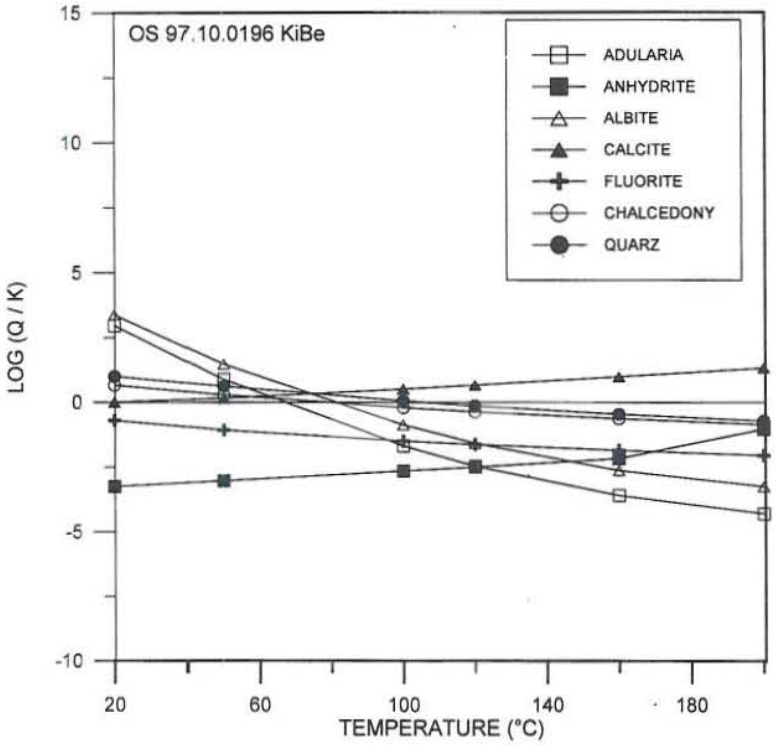

FIGURE 8: Log Q/K vs. temperature for the Fantale 2 hot spring

The chemistry of the hot springs is very similar. Hence, atomic ratios of some selected elements are approximately the same (Table 6). Fantale-2 was chosen to construct the saturation diagram of log Q/K versus temperature (Figure 8). As shown in the figure, few curves for the minerals considered cross the zero line at a temperature approximately between 75 and 90°C, but do not converge at one point. A few other curves intersect at log Q/K > 0 and log Q/K < 0, at about 60-75°C and 100-170°C, respectively. Most of the minerals considered are under-saturated. Calcite supersaturation increases with temperature and quartz shows a tendency of supersaturation in the temperature range 100-120°C. The plot of log Q/K diagram suggests that there is some mixing of hot water with lower temperature waters.

Temperature estimates obtained by the calculation of geothermometers are tabulated in Table 7. The temperature estimated by each type of solute geothermometer gave approximately the same result for both hot springs. The lowest temperature 85°C (average) is estimated by a chalcedony-silica geothermometer (Fournier, 1977) and the highest temperature 180°C (average) was estimated by a Na-K geothermometer (Giggenbach, 1980); other geothermometers considered gave values between the two. The temperature range is still less than the temperature range indicated by the Wonji hot springs. The deeper temperature obtained by the quartz geothermometer compares rather well with the values obtained from Na-K geothermometers by Arnórsson et al. (1983b) and Truesdell (1976) indicating a reservoir temperature of 110-120°C for the samples considered. There is probably some mixing with cold water as discussed above. Therefore, a deep temperature of minimum 130°C might be expected.

More samples were collected from this area than for the other regions. Comparison of the δD and $\delta^{18}O$ values for all samples indicates the range to be -21.1‰ to +43.4‰ in δD and -4.4‰ to 7.33‰ in $\delta^{18}O$ (Figure 4). The two hot springs from this area, Fantale-1 and Fantale-2, have very similar isotopic composition and plot slightly below the local meteoric waterline with deuterium excess of 8.5 and 7.4, respectively. The cold groundwater samples on the other hand have variable isotopic composition ranging from -4.4 ‰ to +0.6‰ in $\delta^{18}O$ and -21.0‰ to +21.0‰ in δD. Composition of the Metehara town precipitation (-2.72‰ in $\delta^{18}O$ and -9.9‰ in δD) collected in 1995 lies within the isotopic range of the groundwater samples. Comparison of d-excess values indicates the range -15.24‰ to 18.00‰, with both extremes being surface waters, i.e. Metehara lake (7.3 in $\delta^{18}O$ and 43.4 in δD) and Kebena river (-2.0 in $\delta^{18}O$ and 2.4 in δD), respectively. The Welinchiti water supply has the lowest δD and $\delta^{18}O$ and plots close to the AAMWL (Figure 4). Welinchiti is located at a higher altitude and further inland than any other samples from the area (Figure 2). Therefore, its low isotopic values are due to both altitude and inland effects. Metehara lake has higher δD and $\delta^{18}O$ values than any other sample from the area due to evaporation effect.

A close examination of the tritium values of the Fantale samples reveals the existence of the following four types of water in terms of relative age.

1. Surface waters and the Metehara town water supply have more or less similar tritium values to the present precipitation. Hence, they contain waters of modern age.

2. Welinchiti water supply and the hot springs, which have much lower tritium values than the present precipitation, contain waters older than 1950.

3. Metehara cold spring has much higher tritium values than the present precipitation and is older than type 1 waters mentioned above. Hence, it contains water from the time of the hydrogen bomb test.

4. Metehara lake (3.9 TU) and Metehara Msq.D.W. (2.2 TU) probably contain mixed waters of pre-1950 and modern precipitation.

As indicated by the similarity of their isotopic and chemical composition, the hot springs most likely originate from the same aquifer. There is no clear evidence either from the chemistry or the isotopic data to explain the hydrological connection of the other samples. A close examination of the chemical and isotopic data from Metehara lake and Metehara mosque dug well, however, suggests a similar hydrological situation. Both samples are alkaline. Metehara lake has a Na/Cl of 3.5 and K/Cl of 1.15, whereas the Metehara mosque dug well has a Na/Cl of 3.2 and K/Cl of 1.16, and they have similar ratios of Mg/Cl and Ca/Cl (Table 6). Therefore, since the dug well is at a lower elevation and is less mineralized than the lake, it is possible that the well can tap water from the lake. The water from the lake moves down to the dug well and mixes with shallow meteoric water infiltrating to the ground from precipitation, and, hence, pH decreases from 9.55 to 9.00; other major cations and anions decrease as well. The isotopic composition also decreases down to -1.14‰ $\delta^{18}O$ and -4.8 ‰ δD due to mixing local precipitation with lower isotopic composition. A sample from the Metehara water supply borehole has a pH of 8.4 which is less alkaline than the mosque dug well sample and is also lower in other major cations and anions concentration. This water could also be slightly affected by the infiltration of the lake. In the future, detailed hydrogeological, hydrological, chemical and isotopic study might be the most important approach to understanding the real hydrological - hydrogeological conditions of the Metehara area.

8.4 Dofan

Dofan is located north of the Fantale geothermal prospect. It is close to the Western Escarpment of the rift valley. The three hot springs sampled are located very close to the Dofan mountain to the west of Awash river. No samples of groundwater and surface waters were taken from this area apart from the three hot springs. The springs have higher discharge temperatures than any other hot springs considered in this study. Analytical results are shown in Table 4. The general geology of the area is as presented in Chapter 4, for the Southern Afar Rift Valley.

The analytical results of the three hot springs are used in different plots shown in Figures 3, 4, 5 and 6. The data plot around the point representing 50% HCO_3, 25%Cl and 25% SO_4 in the triangular plot in Figure 3. Compared to the waters of Wonji and Fantale, the bicarbonate content of the hot springs is less than that of the two areas mentioned above, whereas the chloride content is higher. This may indicate that the Dofan hot springs discharge waters contain a higher proportion of geothermal component than any other hot springs in the Southern Afar region covered by this study.

Comparison of the chemistry of the hot springs indicated no difference for the major cations and anions analysed. The small difference observed for some analyses can be accounted for by analytical error. This suggests that the thermal water of the springs emerges from the same aquifer system and follows more or less the same path and is affected by similar processes until it is discharged at the surface.

A Na-K-Mg triangular plot is used to see whether the hot water is in equilibrium at depth (Figure 6), (Arnórsson, 1991). Two points plot in partially equilibrated waters region, as do those of the Wonji and Fantale hot springs. One of the two samples, Dofan-3, plots very close to the line for fully equilibrated waters. Dofan hot spring-1 plots above the line of a fully equilibrated water. This may be due to analytical error in the Mg determination, as the measured Mg concentration of this sample is much lower than the others, about 0.1 mg/kg compared to 0.67 and 0.98 mg/kg. Based on this diagram, the deep equilibration temperature is between 120 and 140°C.

Since the chemistry of the hot springs is very similar, and atomic ratios of some selected elements are approximately the same (Table 6), the Dofan-2 hot spring, with the highest discharge temperature, was selected to construct the log Q/K vs. temperature diagram shown in Figure 9. The figure shows that most of the minerals are under-saturated. Adularia and albite cross the zero point at different temperatures, and again intersect anhydrite at about 115 and 138°C in the region of log Q/K < 0. The plots for some minerals fall near to the saturation line and calcite is always supersaturated, especially at higher temperatures. The plot of log Q/K diagram suggests that there is some mixing of hot water with lower temperature waters.

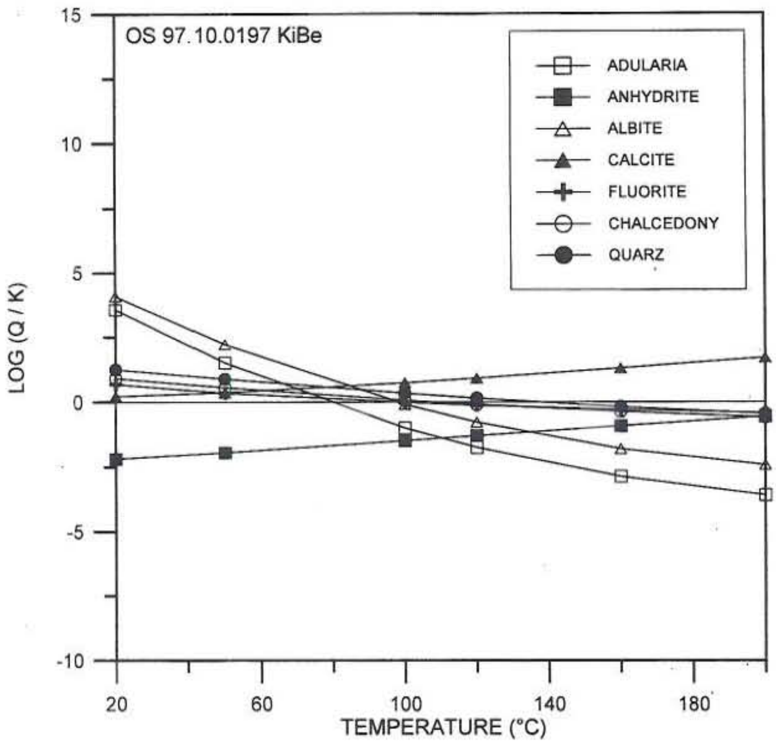

FIGURE 9: Log Q/K vs. temperature for the Dofan 2 hot spring

Deep reservoir temperatures estimated from selected geothermometers are shown in Table 7. The temperature estimated by each type of geothermometer gave approximately the same result for the hot springs. The lowest temperature, 122°C (average), is estimated by the chalcedony silica geothermometer (Fournier, 1977), and the highest temperature, 175°C (average), is estimated by a Na-K geothermometer (Giggenbach, 1980). Other geothermometers considered give values between these two. It is not possible to choose which geothermometer is the most appropriate, but of the silica geothermometers the quartz geothermometer is assumed to be the one. The deep temperature obtained by the quartz geothermometers (143-150°C) does not compare well with the values obtained from the Na-K geothermometers by Arnórsson et al. (1983b) and Truesdell (1976). As discussed above there appears to be some mixing of the waters, which may explain this discrepancy.

Due to a lack of samples, a comparison of isotopic composition of the hot springs with local meteoric water from the area is impossible. The hot springs are similar in their isotopic composition as in chemistry and are, therefore, treated together. The deuterium composition of the hot springs and the Metehara precipitation is very similar (Figure 4), suggesting a recharge from the Metehara area to the Dofan thermal field. The small oxygen shift observed for the thermal field may be due to the reaction of thermal water with rocks high in $\delta^{18}O$. Low tritium content suggests that the waters are older than from 1950.

8.5 Meteka

The Meteka area is located northeast of Dofan. It is the most northerly geothermal prospect considered in this study. From the area, three hot springs, Meteka-1, Meteka-2 and Meteka-3, were sampled for isotope and chemical analysis. The springs have a discharge temperature of about 50°C and are located close to each other in the Meteka village along the road from Addis Ababa to Asseb sea port. No surface and precipitation samples were collected. Analytical results are shown in Table 4.

The analytical data representing the three hot springs are plotted in the Cl-SO_4-HCO_3 triangular plot in Figure 3. The data plots close to the corner of HCO_3, representing about 65% HCO_3 and approximately equal amounts of Cl and SO_4. The chemistry of the Meteka samples is similar to Dofan, except for a slightly lower chloride concentration. The water type is bicarbonate with a little chloride and sulphate.

Comparison of the chemistry of the hot springs indicates no difference for the major cations and anions analysed. This suggests that the hot springs emerge from the same aquifer system and follow more or less the same flowing path and may be affected by similar physical processes which modify the nature of the fluid during its ascent to the discharge zone.

Figure 6 shows that all the three Meteka samples plot slightly below the line for equilibrated waters. If the samples are assumed to be fully equilibrated, the equilibration temperature lies most likely in the range 100-120°C.

The sample from Meteka-2 was chosen to represent the Meteka samples on the saturation index log Q/K versus temperature diagram shown in Figure 10. The curves do not converge in a specific point and most of them cross the equilibrium line at low temperatures. The albite and chalcedony curves are the only ones that cross at log Qm/Km = 0 at about 70°C. The majority of the minerals intersect with each other in the region log Q/K < 0 between 90 and 140°C, similar to that of the Dofan area temperatures. The log Q/K plot suggests that there is some mixing of hot water with lower temperature waters.

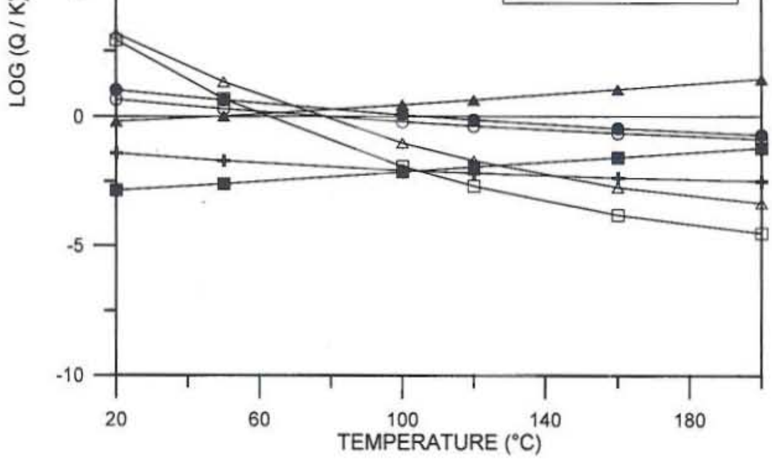

FIGURE 10: Log Q/K vs. temperature for the Meteka 2 hot spring

Deep reservoir temperature is estimated using selected solute geothermometers (shown in Table 7). The lowest temperature, about 80°C, is estimated by the chalcedony-silica geothermometer without steam loss (Fournier, 1977) and the maximum temperature, about 170°C, is estimated by the Na-K geothermometer (Giggenbach, 1980). The deeper temperature obtained by the quartz geothermometer compares very closely to the values obtained from the Na-K geothermometers by Arnórsson et al. (1983b) and Truesdell (1976) and indicates a reservoir temperature of about 110°C for the samples considered. There is probably some mixing with cold water as discussed above. Therefore, a deep temperature of minimum 120°C might be expected.

As samples from cold groundwater from the area were not available, it was not possible to compare isotopic data of the hot springs to that of the local groundwater. The isotopic compositions of the hot springs are very similar to each other in their chemistry (Figure 4). The $\delta^{18}O$ composition of the samples is almost identical. There is a small variation in their deuterium content, especially for Meteka-2, which plots on the AAMW line, whereas the others plot slightly below it. Their isotopic composition is very similar to that of the thermal springs in the Fantale area. Without any information about the isotopic composition of the recharge water, it is not possible to explain the small deviation observed from the meteoric water line. Low tritium concentration suggests that the water is pre-1950.

9. CONCLUSIONS AND RECOMMENDATIONS

1. On the basis of the Cl-SO_4-HCO_3 diagram, the waters range from almost pure bicarbonate to a maximum mixture of about 25% Cl, 25% SO_4 and 50% HCO_3.

2. A reservoir temperature of 110-140°C (average) is indicated by the geothermometers considered.

3. Based on isotopic data of the thermal waters, the following three groundwater systems have been identified: 1) Wonji area groundwater, 2) Fantale and Meteka system, and 3) Dofan groundwater system.

4. Except for the Wonji thermal waters and the Metehara cold spring, the waters are not contaminated with waters from the hydrogen-bomb tests performed during the 1950's. The thermal waters in Fantale, Dofan and Meteka have very low tritium values suggesting that they are pre-1950.

5. Samples from the Dofan area have a similar δD composition to that of the Metehara precipitation. This may suggest that the Metehara area is the recharge area for the Dofan thermal field.

6. The Dofan thermal area is considered to be the most promising area for further studies aimed at electric power generation, followed by Meteka and Fantale.

7. The isotopic and chemical results of Metehara lake and boreholes in Metehara town indicate a hydrological connection between them. Further study of their geochemistry, hydrogeology and hydrology is recommended to verify this assumption.

8. Systematic sampling should be carried out in the future in each of these areas for isotopic and chemical analysis, in order to understand the age and flow patterns of the groundwater systems.

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APPENDIX I: Sampling details

Area	Feature	Sample number
Asela	Kulumsa river	RV-1
	Kulumsa rain	RA-2
	Wonjigora D.G.W	BH-3
Wonji	Awash river	RV- 4
	Koka lake	LK-5
	Nazerat (Town) water supply	BH-6
	Hipoo pool-1	HS-7
	Hipoo pool-2	HS-8
	Hipoo pool-3	HS-9
	Hipoo pool-4	HS-10
Fantale	Kebena river	RV-11
	Bulga river	RV-12
	Metehara lake	LK-13
	Welinchiti (Town) water supply	BH-14
	Metehara (Town) water supply	BH-15
	Metehara (Town) Msq.D.W	BH-16
	Metehara cold spring	CS-17
	Fantale hot spring-1	HS-18
	Fantale hot spring-2	HS-19
Dofan	Dofan hot spring-1	HS-20
	Dofan hot spring-2	HS-21
	Dofan hot spring-3	HS-22
Meteka	Meteka hot spring-1	HS-23
	Meteka hot spring-2	HS-24
	Meteka hot spring-3	HS-25