Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

CHEMICAL AND ISOTOPIC STUDIES OF GEOTHERMAL PROSPECTS, IN THE SOUTHERN AFAR REGION, ETHIOPIA.

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Key words: - Groundwater systems, isotope and chemical study, Southern Afar region, geothermal prospects.

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. Deuterium, tritium and oxygen-18 are most important in separating ground water systems into different types. Based on the isotopic data, three groundwater systems are identified: 1) Wonji area, 2) Fantale and Meteka areas, and 3) Dofan area. Tritium results show that the geothermal waters are not contaminated with tritium waters from the hydrogen-bomb tests performed during the 1950s, 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. Solute geothermometery indicated that the reservoir temperature is in the range of 110-142°C (average). Future studies should give priority to Dofan and Fantale geothermal prospects, followed by Meteka and Wonji.

1. INTRODUCTION

The Ethiopian Rift Valley is part of the Great East African Tertiary-Quaternary rift system. It covers an area of 150,000 km^2 and can be divided into two broad units, the Main Ethiopian Rift and the Afar Rift. The rift floor rises to 1230m a.s.l at Lake Chamo in the south and decreases to 120m b..s. l in the Danakil Depression, in the north. Tectonic fragmentation of the rift floor formed fault swarms, including the Wonji Fault Belt (Mohr,1967).

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

The Southern Afar Rift is located between 8^0N to 12^0N and 39^0E to 41^0E between the Ethiopian Main Rift in the south and the Northern Ethiopian Rift in the north.

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 indicated the presence of high temperature geothermal fluids at shallow depth due to magmatic heat sources (UNDP, 1973). During the last 25 years, different geoscientific studies have been carried out in the Ethiopian Rift Valley. The studies were done for evaluation of geothermal reservoir temperature and identification of recharge areas for the identified geothermal fields. In most cases, the studies were regional. In this study, an attempt was made to oncentrate on the Southern Afar rift valley using the 1993 isotopic and chemical data.

2. PURPOSE AND SCOPE OF STUDY

Isotopic studies require a systematic sampling programme of precipitation, surface waters, cold springs, boreholes, hot springs, geothermal wells and fumaroles for a number of years to understand the hydrological regime and to construct a base map of groundwater systems for a certain region. In light of this, the present work uses the available isotopic and chemical data to interpret the most common hydrological processes in the studied areas.

During 1993, 25 samples were collected. Three from Asela (1 rain, 1 river, 1 dug well), seven from Wonji (1 river, 1 borehole, and 4 hot springs), nine from Fantale (2 rivers, 1 lake, 2 boreholes, 1 cold spring and 2 hot springs), three hot springs from Dofan ,and three hot springs from Meteka (Figure 1.)

3. GEOLOGICAL SETTING

The Afar rift is located NE (9^0N, 40^0E) of the Main Ethiopian Rift. This triangular region is bounded to the SE by the Somalia plateau and to the NE by the Red Sea. Faults of the Main Ethiopian Rift Valley (trending NNE), Gulf of Aden (trending E) and Red Sea (trending NW) penetrate the Afar region. Surface faulting of the Main Ethiopian Rift Valley can be traced as far northeast as Tendaho. From both geological and geophysical evidence it appears probable that narrow spreading zones of 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 this, 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, 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 (UNDP,1973).

4. METHODS OF SAMPLING AND ANALYSIS

4.1 Field sampling procedures

Double capped polyethylene bottles were used for collection of water samples from rain, rivers, lakes, dug wells, boreholes, cold springs and hot springs for isotope and chemical analyses. All hot springs were collected from relatively strong flows and high temperatures. River and lake samples were taken by deepening sampling vessels approximately to a depth of 30 cm. Dug wells and boreholes were sampled from the water level using a bucket and nylon rope. The precipitation sample from

Asela was collected from the nearby meteorological station. Their locality name and features type identifies sampling points. en there is a similar feature type in the same area, a number is given for further identification (Figure 1).

4.2 Field measurements and chemical analysis

A maximum thermometer was used to measure the temperature of the hot springs directly from the point of maximum flow. The pH of the samples were measured using a calomel glass electrode (ORION TYPE) at the sampling temperature. Silica was determined using visual colorimetry based on the blue complex formed with ammonium molybdate reagent.

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, (pH of 3.8), using a micro alkali meter.

5. Analytical results

The samples were analysed at the Isotope Hydrology Laboratory of the International Atomic Energy Agency and results are reported in mg/kg for major cations and anions (Table 1). Results of isotope analysis are reported in the 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. The following general relationship between δD and $\delta^{18}O$ has been established for meteoric water worldwide (Craig, 1961a).

$$\delta D = 8\delta^{18}O + 10 \qquad (1)$$

Deuterium excess is defined from the meteoric water line as

$$d = \delta D - 8\delta^{18}O \qquad (2)$$

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 (Johnson et al., 1989).

6. DISCUSSION

6.1 Methods used for chemical and isotopic interpretation

Triangular plots of Cl, SO_4 and HCO_3 are used for classification of water types and choosing geothermometers when equilibrium conditions and sub-surface temperatures are considered. Figure 2 shows results of the present study on Cl - SO_4 - HCO_3 diagram,. 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.

The study of conservative elements aids in evaluating the origin and possible flow path of the groundwater system as well as marking processes such as dilution and evaporation. Isotopic ratios, tend to be very conservative and are good indicators of the origin of flow, mixing and evaporation (Craig, 1961b). The $\delta^{18}O$ are similarly useful, except that oxygen isotopes are exchanged between hot rock and the circulating meteoric water to produce an “oxygen isotope shift” to higher ^{18}O content in the water and a reverse shift to lower ^{18}O content of the rock.

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

$$\delta D = 8\delta O^{18} + 12.5 \text{ AALMWL} \qquad (3)$$

Isotopic composition of all the samples used for the study is compared to the line defined by equation (3) in Figure 3. All the samples plot close to the line, except the sample from Lake Metehara, which show considerable oxygen isotope shift. As there is not enough isotopic data available for precipitation, only a general conclusion can be drawn regarding the origin and flow pattern of groundwater systems.

Chemical geothermometers of chalcedony, quartz and Na - K have been used to estimate the reservoir temperature of the geothermal systems (Table 2). Interpretation will be discussed in terms of the geographic area.

6.2 Wonji

The Wonji area is located in the Southern Afar rift valley. The area is mainly characterised by NNE trending fault swarms (Mohr, 1967). Seven samples were collected during 1993 and analysed for their isotope and chemical constituents. These includes, Awash river 1, Koka hydro electric dam 1, Nazareth town water supply borehole 1, and Hippo Pool hot springs 4, Analytical results are shown in Table 1.

The analytical results are plotted on the Cl-SO_4-HCO_3 diagram Figure 2; where, all points are very close to the bicarbonate corner. 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 7.0 mg/kg for Koka electric power dam to 29.3 mg/kg for Nazareth town water supply borehole. The chloride content of the hot springs is in the range of 23.5 mg/kg to 27.5 mg/kg. This shows, that the hot springs discharge waters that are mostly meteoric in origin and are heated by the regional high positive heat anomaly and/ or by shallow magma intrusion which is the main heat source in the Ethiopian Rift Valley (UNDP, 1973). Na-K-Mg triangular plot (Arnorsson, 1991), is used to see whether there is equilibration of the hot springs waters at depth (Figure 4). Samples of the hot springs plot near the boundary line between immature waters and partially equilibrated waters. Based on the plot, the equilibration temperature at depth is estimated between 140°C and 160°C.

The temperatures estimated using selected geothermometers are shown in Table 2. The lowest temperature, about 113°C (average) is estimated by the chalcedony silica geothermometer (Fournier, 1977) and the highest temperature approximately 199°C (average) is estimated by the Na - K geothermometer (Giggenbach, 1980). The deeper temperature obtained by the quartz geothermometer compares rather well with the values obtained from Na / K geothermometers by (Arnorsson et al., 1983b) and (Truesdell, 1976) indicating a reservoir temperature of 134°C-143°C for the samples. There is probably some mixing with cold water as discussed above, therefore a minimum deep temperature of 150°C might be expected.

All isotopic data, including samples from Wonji area are entered in Figure 3, using Addis Ababa Meteoric Water line (AAMWL) for comparison as a local meteoric water line. The Hipoo Pool hot springs are very similar in $\delta^{18}O$ (-2.00‰), whereas considerable range is observed in their δD composition (-7.4‰ to +6.7‰). Furthermore the Nazareth 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 water line, indicating slome evaporation.

Figure 3 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 3). The high tritium content of the hot springs suggests that the springs contain a component of water from the hydrogen bomb tests.

The three hot springs Hippo pool 1, 2, and 4 have d- excess of 12.08‰, 10.04‰ and 9.00‰ respectively. Exceptionally, Hippo pool -3 has much higher deuterium excess, about 19.58‰. The three hot springs can be treated as groundwater system similar to that of the Wonjigora and the Nazareth cold groundwaters. It is difficult to explain the high δD values for Hippo pool 3, since there is no significant difference between.the hot springs Based on this information, the hot springs emerge probably from the same aquifer system.

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

6.3 Fantale

The Fantale area is located in the Southern Afar region and 2 rivers, 1 lake, 1 dug well, 2 boreholes, 1 cold spring and 2 hot springs were sampled. Analytical results are shown in Table 1. The analytical results representing the area are plotted in Figure 2. Most of the data points plot in the region of HCO_3. They have higher chloride content than the Wonji waters. Therefore, the waters are bicarbonate type with a little mixture of chloride and sulphate.
Comparison of the chemistry of the different types of samples can lead to groupings of the samples based on similarity of chemical compositions for the major cations and anions. Three distinct chemical groups can be observed, group 1- rivers, group 2- Metehara Lake and Metehara mosque dug well and group 3- the hot springs. The remaining three are not chemically similar to any of the groups. In the Na - K - Mg triangular diagram (Figure 4), the hot springs plot in the region of partially equilibrated waters. Temperatures of 100 to 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 of 120° - 140°C, lower than the Wonji thermal water.

Temperature estimates obtained by calculation of chemical geothermometers are shown in Table 2. The lowest temperature 85°C (average) is estimated by chalcedony - silica geothermometer (Fournier, 1977) and the highest temperature 180°C (average) estimated by Na - K geothermometer (Giggenbach,1980). The deeper temperature obtained by the quartz geothermometer compares rather well with the values obtained from Na - K geothermometers by (Arnorsson et.al., 1983b) and (Truesdell, 1976) indicating reservoir temperature of 110C- 120°C for the samples considered.

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 3). The two hot springs Fantale -1 and Fantale -2 have very similar isotopic composition and plot slightly below the local meteoric water line with d 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. The Metehara town precipitation (-2.72‰ in $\delta\ ^{18}O$ and -9.9‰ in δD) lies within the isotopic range of the groundwater samples. Comparison of d- excess values indicates the range -15.24‰ to 18.00 ‰, i.e Metehara lake (7.3 $\delta^{18}O$ and 43.4 δD) and Kebena river (-2.0 $\delta^{18}O$ and 2.4 δD) respectively. The Welenchiti water supply has the lowest δD and $\delta^{18}O$ and plots close to the AALMWL (Figure 3). Welenchiti is located at a higher altitude and further inland than any other samples from the area. Its lower isotopic values are due to both altitude and inland effects. Metehara Lake has the highest δD and $\delta^{18}O$ values than any other samples due to evaporation t.

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

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

2. Welinchiti water supply and the hot springs, which have much lower tritium values than the present precipitation, containing 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 and contains the most water from 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 from 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, where as the Metehara mosque dug well has a Na/Cl of 3.2 and K/Cl of 1.16, and they have even similar ratios of Mg/Cl and Ca/Cl . Therefore, since the dug well is at lower elevation and is less mineralised 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, and other major cations and anions decreases as well. The isotopic composition also decrease down to -1.14‰ $\delta^{18}O$ and -4.8 ‰ δD due to mixing with local precipitatio nf lower isotopic composition. Sample from the Metehara water supply borehole has a pH of 8.4 less alkaline than the mosque dug well sample and is also lower in other major cation and anion concentrations. 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 understand the real hydrological - hydrogeological conditions of the Metehara area.

6.4 Dofan

Dofan is located north of the Fantale geothermal prospect. It is close to the western escarpment of the rift valley. The springs have higher discharge temperatures than any other hot springs considered in the study. Analytical results are shown in Table 4. The analytical results of the hot springs are used in different plots shown in Figure 2, 3,and 4. The data plots around the point representing 50% HCO_3, 25% Cl and 25% SO_4 in the triangular plot in Figure 2. 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 shows that the Dofan hot spring waters contain higher proportions of a geothermal component than any other hot springs in the Southern Afar region covered by the study.

Comparison of the chemistry of the hot springs indicated no significant difference for the major cations and anions analysed. This suggests that the thermal waters 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.

Na-K-Mg triangular plot is used to see whether the hot water is in equilibrium at depth (Figure 4). Two points plot in partially equilibrated waters region as that 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 fully equilibrated waters. This is probably 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 mg/kg and 0.98 mg/kg. Based on this diagram, the deep equilibration temperature is between 120°C and 140°C.

Deep reservoir temperatures estimated from selected geothermometers are shown in the Table 2. The lowest temperature 122°C (average) is estimated by chalcedony silica geothermometer (Fournier, 1977) and the highest temperature 175°C (average) is estimated by Na-K geothermometer (Giggenbach,1980). The deeper temperature obtained by the quartz geothermometers (143°C-150°C) don´t compare very well with the values obtained from Na / K geothermometers by (Arnorsson et.al., 1983b) and the reason is not clear.

Due to 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 3), suggesting a recharge from the Metehara area to the Dofan thermal field. The small oxygen shift observed for the thermal field is possibly due to the reaction of thermal water with rocks high in ^{18}O. Low Tritium content suggests the age of the waters to be older than 1950.

6.5 Meteka

The Meteka area is located NE of Dofan. From the area, three hot springs Meteka -1, Meteka -2 and Meteka -3 were sampled for isotope and chemical analysis. The springs have discharge temperature of about 50°C and are located close to each other in the Meteka village. No surface and precipitation samples were collected. Analytical results are shown in Table 4. In Figure 2, the data plot close to the HCO_3 corner, representing about 65% HCO_3 and approximately equal amount of Cl and SO_4. The chemistry of the Meteka samples is similar to the Dofan samples, apart from slightly less chloride concentration. The water type is bicarbonate, but with a little mixture of chloride and sulphate.

Comparison of the chemistry of the hot springs indicates no significant difference for the major cations and anions analysed. This shows the hot springs emerge from the same aquifer system and follow more or less the same flow path and may be affected by similar physical processes which modifies the nature of the fluid, during its ascent to the discharge zone. Figure 4 shows that all Meteka samples plot slightly below the line for equilibrated waters. If the samples are fully equilibrated, the equilibration temperature lies most likely in the range 100°C to 120°C.

Deep reservoir temperature estimated using selected solute geothermometers are shown in Table 2. The lowest tempera-ture is estimated by the chalcedony-silica geothermometer with out steam loss (Fournier, 1977) gave about 82°C (average) and the maximum temperature estimated by the Na-K geothermometer (Giggenbach, 1980) is about 170°C (average). The deeper temperature obtained by the quartz geothermometer compares very well to the values obtained from Na - K geothermometers by Arnorsson et.al., (1983b) and indicates a reservoir temperature of 110°C- 112°C for the samples considered. There is probably some mixing with cold water as discussed above; therefore a deep temperature of 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 and chemical composition of the hot springs is very similar to each other. The $\delta^{18}O$ composition of the samples is almost identical. There is small variation in their deuterium content, especially for Meteka -2, which plots on the AALMWL line, whereas the others plot slightly below it. 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 the age of the waters is older than that of the Dofan waters.

7. CONCLUSIONS AND RECOMMENDATIONS

1. Based on isotopic data of the thermal waters, three groundwater systems have been identified as Wonji, Fantale and Meteka,and Dofan groundwater systems.

2. On the basis of 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

3. Reservoir temperatures of 110-140°C (average) are indicated by the geothermometers.

4. Except for Wonji and Metehara cold spring waters, the waters are not contaminated with waters from the hydrogen - bomb tests

5. Samples from the Dofan area have similar δD and $\delta^{18}O$ composition to that of the Metehara precipitation. This may suggest the Metehara area as the recharge area for the Dofan thermal field.

6. The Dofan thermal area is the most promising area for further study 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 hydrological connection between them.

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

ACKNOWLEDGEMENTS
Most of work is the result of Fellowship award by International Atomic Energy Agency (IAEA) for specialized training on groundwater hydrology. The award is gratefully acknowledged and I am grateful to the Ethiopian Institute of Geological Survey (EIGS) for giving me the opportunity to attend the training.

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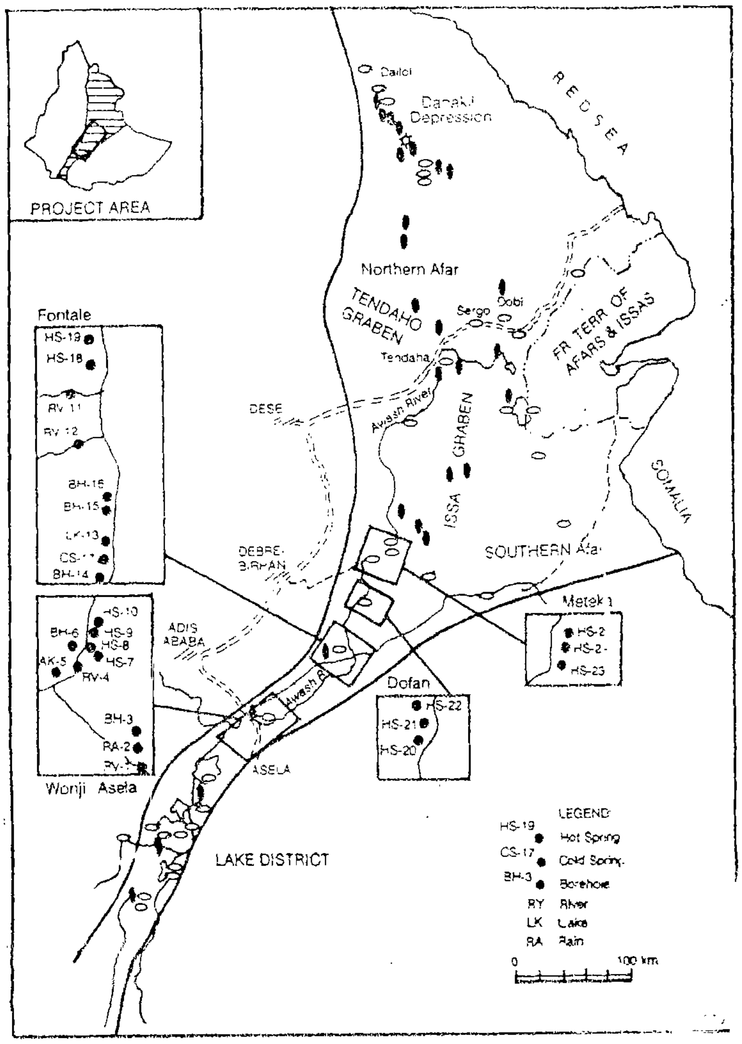

Figure 1. Approximate location of sampling sites (not scaled)

TABLE 2: Results of selected solute geothermometer calculations using measured concentrations of hot springs

Area	Typ. feature	CH	CHs	QRZT	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	Fantale H. Sp1	85±10	88±10	114±10	113±10	130±10	119±10	180±10
	Fantale H. Sp2	85±10	88±10	114±10	113±10	133±10	122±10	182±10
Dofan	Dofan H. Sp1	125±10	120±10	150±10	143±10	129±10	118±10	178±10
	Dofan H. Sp2	124±10	119±10	149±10	143±10	134±10	123±10	183±10
	Dofan H.Sp3	118±10	115±10	144±10	138±10	116±10	105±10	168±10
Meteka	Meteka H. Sp1	83±10	86±10	112±10	112±10	122±10	111±10	173±10
	Meteka H. Sp2	82±10	86±10	111±10	111±10	120±10	109±10	171±10
	Meteka H.Sp3	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 (Arnorsson et.al. 1983a)
QRZT = Quartz no steam loss (Fournier,1973) ; QRZTs = Quartz maximum steam loss (Fournier, 1977).
Na-K1 = (Arnorsson et.al., 1983b); Na-K2 = (Truesdell, 1975); Na-K3 = (Giggenbach,1980).

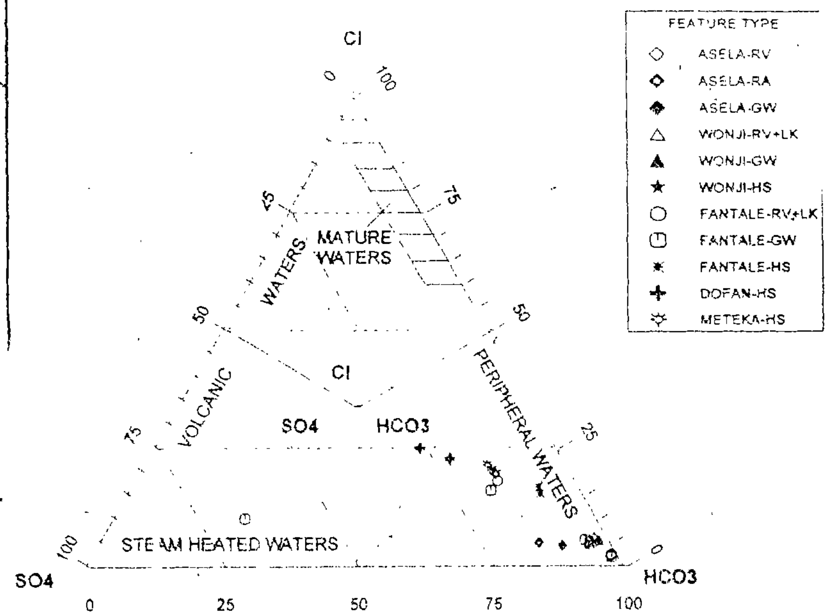

Figure 2. A Cl-SO_4-HCO_3 diagram for the Southern Afar waters

TABLE 1: Analytical results of major constituents for Asela,Wonji and Fantale areas, concentrations mg/kg) and conductivity (μs)

ASELA

Typ. feature	Cond.	PH	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	F	SIO_2
Kulumsa.river	ND	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.DW	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

Typ.feature	Cond.	PH	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	F	SIO_2
Awash . R	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

Typ. feature	Cond.	PH	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	F	SIO_2
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..	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 H. Sp1	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 H. Sp2	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

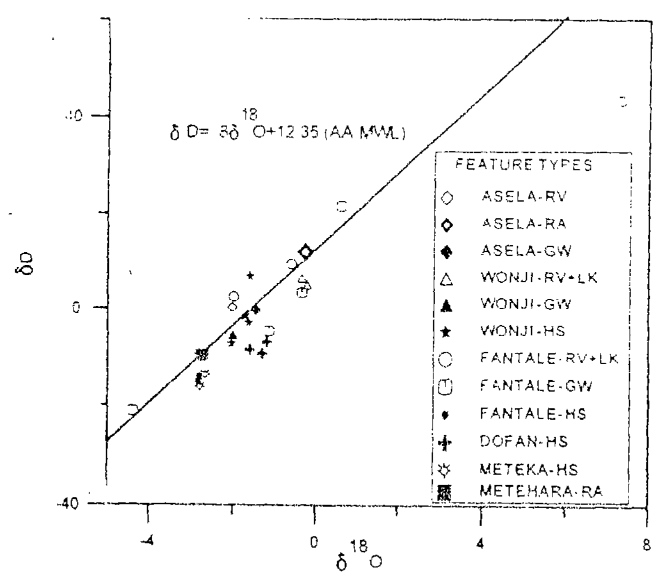

Figure 3. A δD vs. $\delta^{18}O$ plot for all the collected samples

TABLE 3: Results of isotope analysis and deuterium excess values

Area	Typ.feature	$\delta^{18}O$	δD	TU	δ 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.DW	-1.5	-0.4	5.7	0.4	11.3
Wonji	Awash . R	-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 H. Sp1	-2.8	-14.1	0.3	0.3	8.5
	Fantale H. Sp2	-2.9	-15.4	0.3	0.3	7.4
	Metehara rain†	-2.7	-9.9	ND	ND	11.9
Dofan	Dofan H. Sp1	-1.3	-9.4	0.6	0.3	1.1
	Dofan H. Sp2	-1.2	-7.1	0.5	0.3	2.5
	Dofan H.Sp3	-1.6	-8.6	0.5	0.3	4.3
Meteka	Meteka H. Sp1	ND	-16.3	-0.1	0.3	6.1
	Meteka H. Sp2	-2.8	-9.5	0.1	0.3	13.1
	Meteka H.Sp3	-2.7	-13.8	-0.1	0.2	7.6

† Metehara rain sample from 1995 isotope analysis data.
ND = not determined

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

DOFAN

Typ. feature	Cond.	PH	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	F	SIO_2
Dofan H. Sp1	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
Dofan H. Sp2	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
Dofan H.Sp3	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

Typ. feature	Cond.	PH	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	F	SIO_2
Meteka H. Sp1	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
Meteka H. Sp2	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
Meteka H.Sp3	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

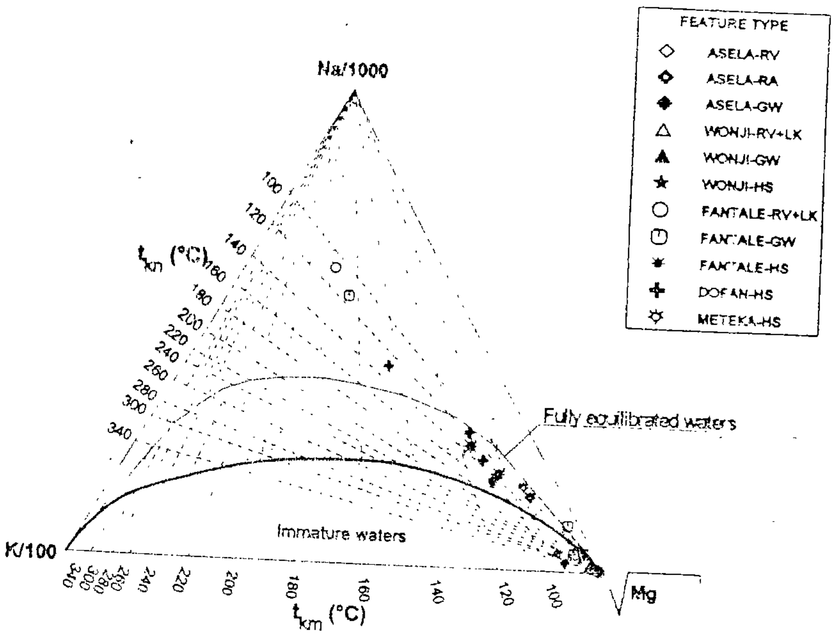

Figure 4. Na-K-Mg diagram for the Southern Afar waters