GEOCHEMISTRY OF THE TENDAHO GEOTHERMAL FIELD, ETHIOPIA

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Abstruct

The Tendaho geothermal field is located in the Afar triangle (Northern Afar) about 700 km north-east of Addis Ababa.

The Afar triangle is an area of active extensional tectonics and basaltic magmatism from which the Gulf of Aden, the Red Sea, and the Ethiopian rift systems radiate . Normal faults and open fissures are the principal elements of the Afar tectonics.

In the Tendaho geothermal field, three deep (1811m-2100m) and three shallow (466m-516m) exploratory wells were drilled, of which four wells (one deep and three shallow wells) are found to be potentially productive. The waters of productive wells are typical of Na-Cl geothermal waters with reservoir temperature of about 220-250°C. At Tendaho, a production test and feasibility study is currently in hand.

The main objective of the present study is mainly to identify the recharge and the sub-surface temperature of the Tendaho geothemal systems. Previous work had been reviewed and water samples had been collected for chemical and isotope analysis in order to get full information about the Tendaho geothermal system. After using different chemical and isotopic techniques, the following conclusions are given.

- The water type of the Tendaho geothermal field is dominantly Na-Cl, neutral to alkaline geothermal water.
- The average reservoir temperature of the systems is about 220°C-250°C.
- The isotope result has indicated two recharge zones, the Ethiopian plateau and the Lakes district through the Southern Afar.

1. INTRODUCTION

The application of chemical and isotope techniques is essential to get information about temperature, origin of the fluid and the types of the reservoir fluid, which may not be obtained with geological or geophysical techniques. The area of study is Northern Afar (Fig 1). Six wells (three shallow (466m-516m) and three deep wells (1811m-2100m)) were drilled in the Tendaho geothermal field. Among these four wells (one deep and three shallow wells) are potentially productive.

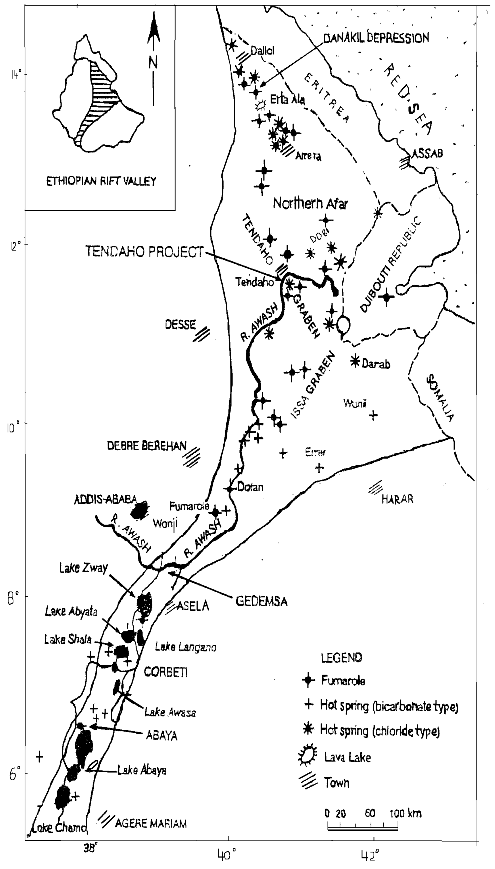


Figure 1: Geothermal areas in the Ethiopian rift valley

The objective of this investigation is to get information on the recharge of the Tendaho geothermal field. The study has been carried out, during three months training at the International Institute for Geothermal Research, in the frame of an agreement between the Ethiopian Institute of Geological Survey (EIGS) and the International Atomic Energy Agency (IAEA).

For this study, 80 water samples for isotope analyses and 76 water samples for chemical analyses were taken from high and low lands of Ethiopia (2600-110m.a.s.l). The samples have been analysed in Vienna for isotopes and in Ethiopia for the chemical elements. The discussions focus mainly on the Tendaho geothermal field and the Alalobeda hydrothermal system.

1.1 General Geology of Tendaho

The Afar Triangle is an area of active extensional tectonics and basaltic magmatism from which the Gulf of Aden, the Red Sea and the Ethiopian rift systems radiate. Normal faults and open fissures are the principal elements of the Afar tectonics. Most of the Afar Triangle is covered by a Pliocene to early Pleistocene (approximately 4-1 Ma) basalt suite with minor rhyolite centres, which is labelled the Afar Stratoid Series (Varet et al., 1975).

The Northwest trending Tendaho Rift is a southern portion of the Erta Ale-hararo Manda rift system, which extends the active tectonics of the Red Sea to the south. Its width of around 50 km is comparable to that of many continental rifts. The flanks of the Tendaho rift are in the Afar Stratoid Series. The rift is filled with lacustrine and alluvial deposits and with post-Stratoid basalt flows. This filling is topped by recent volcanoes, among which are the historically active Kurub and Dama Ali Volcanoes. Abundant hydrothermal activity, both present and fossil are recognisable in particular along a master border fault at Alalobeda (Northeast of Tendaho).

The Dobi graben is bounded both by inward dipping (synthetic) and outward-dipping (antithetic) normal faults frequently associated with flexures tilted toward the rift. Dobi rift differs from Tendaho in its lesser size, steeper flanks and the absence of recent extrusive activity.

2. Previous work

Geothermal Exploration in Ethiopia began in 1969 with a regional geological-volcanological mapping and manifestation inventory jointly by the United Nations Development Program and the Ethiopian Government. This regional assessment covered the whole of the Ethiopian Rift valley and the Afar depression of Ethiopia (see Fig.1).

Water samples for chemical and isotopic analyses were collected from the northern Afar region in 1969 and 1970 (Gonfiantini et al., 1973). Later, Craig (1977) conducted a regional chemical and isotopic study covering almost the whole of the Ethiopian Rift valley. Environmental isotopes of 18O, D, tritium, 4He, 14C and 13C were analyzed and interpreted. Craig confirmed the presence of a high temperature deep circulating geothermal fluid, usable for electric power generation.

On the basis of several years of exploration activities which included geological, geophysical and geochemical investigations, three prospective areas were selected; (i) Dallol in the Afar Depression; (ii) Tendaho in Northern Afar; and (iii) the Lakes District (Aluto-Langano, Shalla-Corbetti and Lake Abaya).

Due to logistic reason the Aluto-Langano in the lakes district and Tendaho in the Northern Afar were selected as the first and second priorities respectively.

An Italian State company, Aquater performed a regional isotopic study and geochemical monitoring of the deep wells of Tendaho (TD-1 and TD-2), in 1994-95. The isotopic study was mainly focussed on the Tendaho graben and the western escarpment of the Ethiopian Rift Valley to identify the recharge area of the Tendaho geothermal field. It was concluded that the Tendaho geothermal field is not recharged from the western escarpment and further studies were recommended. Isotopic studies of liquid water and gas samples collected from the deep 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) had reviewed all the available isotopic and chemical data, starting from UNDP 1973, during his mission as an IAEA project expert. He has interpreted δ^{18}O, δD and Tritium data from the Ethiopian Rift Valley and suggested the possible existence of regional groundwater which flows from the main Ethiopian Rift Valley (Lakes District) in the south to Northeast through the South Afar region recharging the Tendaho graben.

D`Amore et al (1997) performed gas and isotope interpretation of the Tendaho geothermal system. From the isotopic investigation the suggested recharge area is in the order of 2000-2500 m.a.s.l. on the plateau.

3. GEOCHEMISTRY

3.1 ION BALANCE

The ion balance of 76 samples has been checked and most of the data shows an error of 1%. The highest margin of error had been for the ion balances from Alalobeda springs that have 2-4% error. Therefore according to the ion balance all the data are within the normal range.

3.2 WATER TYPE

The chemical analysis was made in the Central Geological Laboratory, Ministry of Mines and Energy, Addis Ababa, Ethiopia. Based on the analysis the Cl-SO4-HCO3 plot was made and used to distinguish the water type (Figure 2). By inspection of the diagram, three groups of waters can be distinguished. Those are:

a) Fourteen samples of sodium chloride type water from low land of Tendaho area, that are seven springs of Alalobeda, four springs of Dobi, Tendaho gradient borehole (t.g.b.) and Begadeloma lake and spring. The Alalobeda springs and the Tendaho t.g.b. Exhibit relatively high sulphate content; according to D´Amore

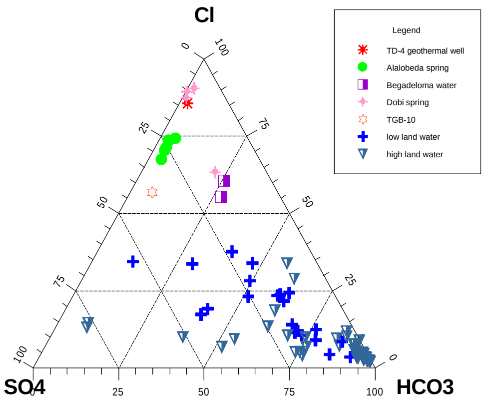


Fig 2. Cl-SO4-HCO3 plot

et al. (1997) this sulphate is generated by the circulation of relatively deep recharge waters inside the large sedimentary surface sequence.

b) Six of the samples plot in sulphate or steam heated water fields, (two from Awaytu springs, Loggia River, Det Bahri well, Dubti Tade well and Abune Aregawi spring).

c) The remaining 57 samples are located in the bicarbonate field.

These waters of (b) and (c) are mainly immature waters that have no significant value as geothermal water.

All hot waters of (a) sampled in the area of Tendaho are geothermicaly mature enough to be typical geothermal chloride water neutral to slightly alkaline, but with a significant amount of sulphate.

3.3 EVALUATION OF WATER-ROCK EQUILIBRIA

The Giggenbach's 1988 Na/1000-K/100-√Mg triangular diagram is essentially based on the temperature dependence of equilibria among the minerals K-feldspar, mica, chlorite and the three cations Na^+, K^+, and Mg^{++}. Relative Na, K, Mg contents of water in full equilibrium with stable mineral systems provides useful reference values to assess the degree of attainment of fluid-rock equilibrium in natural systems.

The fluid composition of hot and cold springs bore holes of the Tendaho geothermal field, shallow wells and the surrounding lakes and rivers have been plotted in Figure 3.

The result shows that only TD-4 water is mature, and the Alalobeda, Dobi and Begadeloma springs are partially equilibrated. And their temperature ranges from 120 to150°C for the Dobi and Bagadaloma springs, and from 150 to 220°C that of the Alalobeda springs.

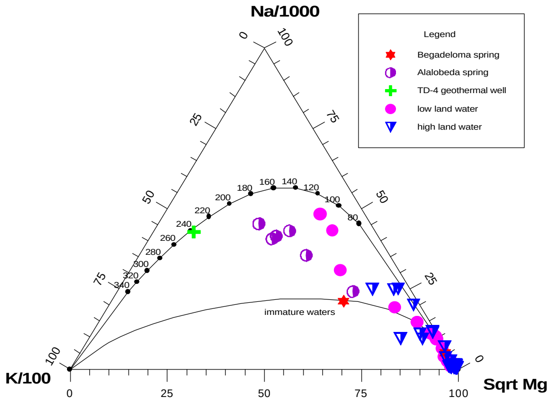


FIGURE 3 : Na-K-Mg PLOT

Observing the two triangular diagrams of Giggenbach in figure 2 and 3, it is obvious that these three areas are characterised by the occurrence of Na-Cl type but less mature water compared to geothermal water of TD-4.To get a better understanding of water-rock equilibria, the saturation indices of selected samples were computed, using SOLMINEQ.88 computer program. These computed values show possible thermodynamic equilibria between the solution and minerals, which could help to define the composition of the reservoir.

Reaction List of figure 4

--1-- Lmt =(CA++/H+^2)+3H2O+2aQz+Kln
--2-- Wrk=(CA++/H+^2)+H2O+2aQz+Kln
--3--2Czo+H2O=4(CA++/H+^2)+3Kln
--4-- Cc=CO2+H2O+(CA++/H+^2)
--5-- 2H2O+Wrk=Lmt
--6-- 10H2O+2Czo+6aQz=3Lmt+(CA++/H+^2)
--7-- 6aQz+2Czo+4H2O=(CA++/H+^2)+3Wrk

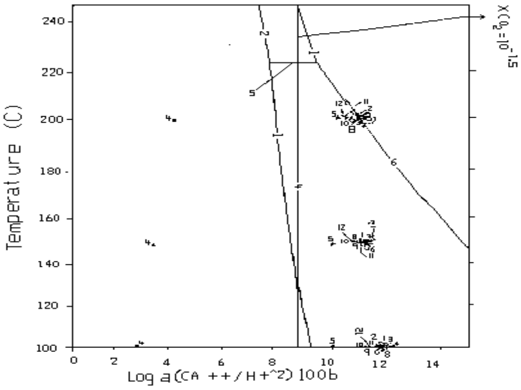


Figure 4: Temperature versus Log a(Ca++/H^2) of 7 Alalobeda springs, 4 Dobi springs and Begadeloma spring at 100 bar.

1,2,10,11 - Dobi Spring, 3,4,5,6,7,8,9 - Al-1 to Al-7, and 12-Begadeloma.

When examining the equilibria of hydrolysis reactions of alumino-silicates, the concentration of monomeric aluminium species must be known, but in our case aluminium and iron were not analysed. To bypass this problem a suitable activity diagram has been constructed in Figure 4.

The diagram represents the stability of some Ca-Al-Fe-silicates as a function of temperature and log $(aCa^{++}/a2H^{+})$. The Fe-bearing mineral epidote is represented in the diagram by using a modified activity of the mineral clinozoisite assuming a pistacite (Fe-epidote) mole fraction of 0.4. The choice of the diagram has been made on the basis of the hydrothermal mineral assemblage found in the core sample of the geothermal well at Tendaho: wairakite, epidote, andraditic garnet and prhenite are found together with quartz, albite and chlorite (Gianelli et al., 1998). The computed log $(aCa^{++}/a2H^{+})$ ratios of the waters of Alalobeda and Dobi plot in the field of laumontite at temperatures lower than 200°C, and close to the boundary laumontite-epidote at a temperature of approximately 200°C. This temperature roughly corresponds to the reservoir temperature of the Tendaho geothermal field, which is from 220 to 250°C.

In order to check the stability of chlorite (a common mineral in the Tendaho core samples) an activity diagram of log a(Mg++/H+) Vs log a (Na+/H+) at different temperatures have been constructed and shown in fig. 4a, 4b and 4c.

Reaction list for figures of 4a,4b and 4c
--1-- Cln+3aQz+2(NA+/H+)=5(Mg++/H+^2)+8H2O+2lAb
--2-- Kln+4aQz+2(NA+/H+)=H2O+2lAb
--3--Tc=3Mg++/H+^2)+4H2O+4aQz
--4-- Cln=5(Mg++/H+^2)+7H2O+aQz+Kln
--5-- 4Cln+2(NA+/H+)=20(Mg++/H+^2)+29H2O+3Kln+2lAb

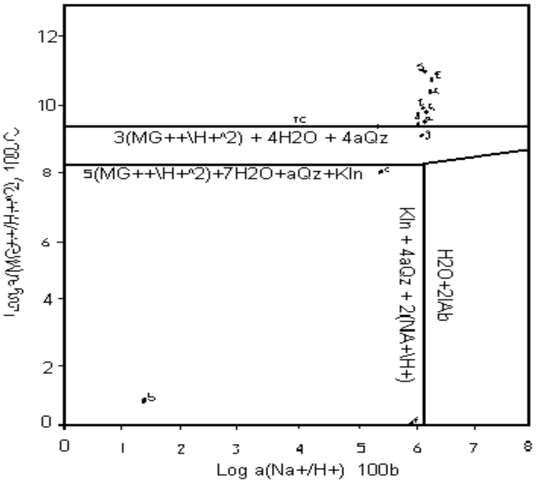


Figure 4a:

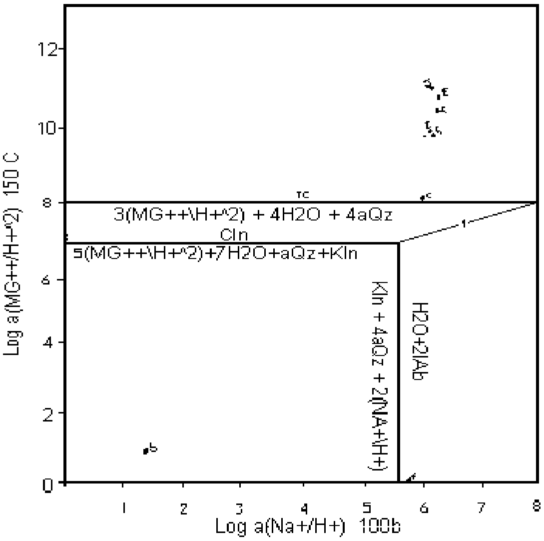


Figure 4b

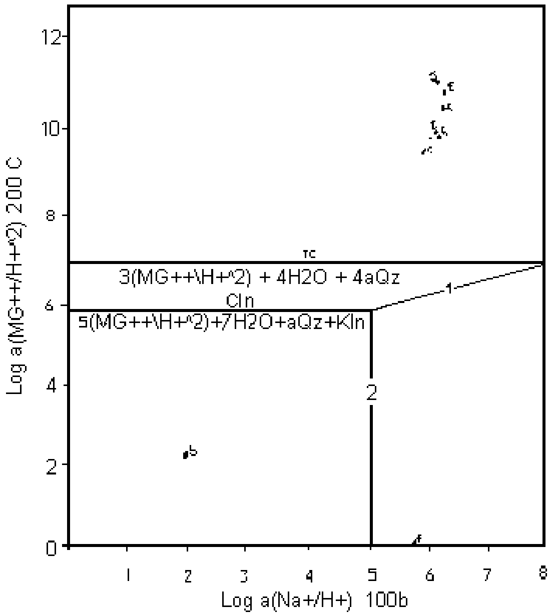


Figure 4c:

Log a(MG++/H+^2) versus Log a(NA+/H^2) of 7 Alalobeda, 4 Dobi and a Begadeloma springs at 100 bar and 100,150^200oC.

a - Al-1, b - Al-2, c- Al-3, d- Al-4, e-Al-5, f- Al-6, g- Al-7,
h- DS-a, I- DS-b, j- DS- c, k- DS-d Where as Al=Alalobeda, DS=Dobi Spring

Clinochlore is stable for a temperature greater than 150°C with the exception of AL-2 spring, which is in the field of the kaolinite for the given three temperatures of 100,150 and 200°C.

4. SOLUTE GEOTHERMOMETRY

Several empirical geothermometers are based upon the relative cation and silica concentration in the solution, which can be used for those water attained mineral-solution equlibria. suitable waters for geothermometric calculations have been selected Based on the Cl-SO4-HCO3 triangular diagram of figure 2 and Na-K-Mg triangular diagram of Giggenbach figure 3. Using SOLMINEQ.88 programs the following temperatures are observed and given in Table 1.

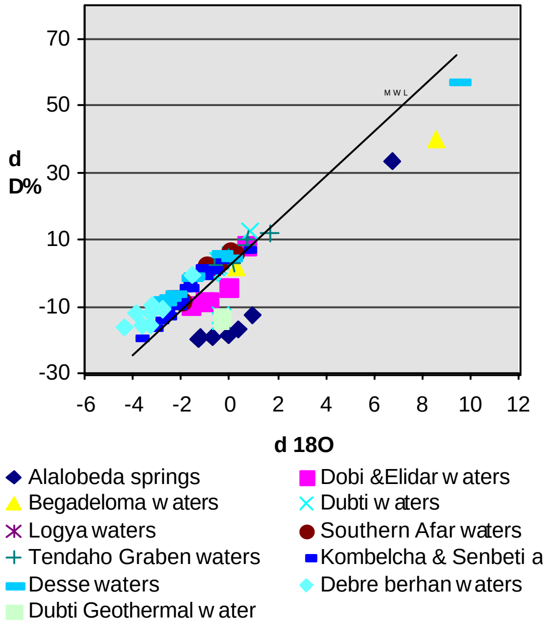
Sample Name	SiO_2 Temp. conductive	SiO_2 Temp. adiabatic	Na/k temp.	+1/3 log (√(Ca)/Na)
Dubti Tade well	116	115	80	96
Dubti Garage well	126	123	69	88
Dubti Tele well	121	119	86	101
Dubti Ayadrus well1	123	121	76	96
Dubti Addis Ketema well1	119	117	82	95
Loggia well1	116	115	81	92
Upper Mile well1	111	110	139	116
Lower Mile well1	116	115	145	119
Harsis well1	131	128	100	105
Sogea well1	132	129	161	140
Loggia well3	105	105	77	88
Asayita well2	100	101	116	135
Asayita well1	105	105	116	133
Serdo Gohela well	120	118	281	180
Hayu (dechi otto) well	101	102	155	129
Lake agadaloma	177	166	209	273
Bagadaloma spring	127	124	208	207
Det Bahari well1	122	120	92	107
Det Bahari well2	133	129	174	139
Elidar well	132	128	64	81
Dobi spring A	151	144	119	129
Dobi spring B	155	147	122	131
Dobi spring C	121	119	142	158
Dobi spring D	147	141	163	171
Alalobada spring1(1)*	227	206	181	174
Alalobada spring 2(24)*	240	216	177	172
Alalobada spring 3(6)*	290	255	187	179
Alalobada spring 4(8)*	158	150	181	175
Alalobada spring 5(9)*	162	154	180	174
Alalobada spring 6(78)*	225	204	181	175
Alalobada spring 7(16)*	226	205	165	163

Table 1: Geothermometric results of the selected areas of Tendaho and the surroundings.

The temperature using the adiabatic silica geothermometer for the Alalobeda springs exhibits lowers temperature compared to the conductive and the Na/K geothermometry. The maximum calculated temperature using adiabatic silica geothermometry observed in Alalobeda spring-3 is 255 °C and the minimum is 150 °C in Alalobeda spring-4. Both springs show a bit higher and lower temperature than the average temperature of Alalobeda which has average temperature of approximately 199 ± 35 °C. Despite the uncertainty of the standard deviation, the average temperature is close to that of the reservoir. For the Begadeloma spring the Na-K geothermometry is 208°C and on the contrary the silica adiabatic temperature is 124°C, this low silica temperature could be due to low surface temperature, which favour to rapid local equilibration of silica. Ca and Mg corrections have been also applied, but the geothermometric results do not change significantly, and for this reasons the Mg-corrected result is omitted and only the Ca correction is reported in Table 1. In this case a high sub surface geothermal anomalies and close to the temperature of geothermal wells observed in the Alalobeda and Begadeloma springs.

5. ISOTOPIC DATA AND RESULTS

From the investigated isotopic plot in Figure 5, three geochemically interesting areas have been observed, those are the Tendaho geothermal field, the Alalobeda springs, and the Dobi springs.



Furthermore, the Begadeloma Crater Lake and Lake

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[*] numbers given by UNDP 1973

Hayk are also interesting features. The waters of these lakes show a possible surface evaporation. The Tendaho geothermal field and the Alalobeda springs show $\partial^{18}O$ shift that could be either a water rock interaction in the deep reservoir rock or a possible mixing with magmatic fluids. The presence of magma contribution in the geothermal fluids of Tendaho has been proposed by D'Amore et al. (1997), on the basis of gas geochemistry.

The Alalobeda hydrothermal system is water- rather than rock-dominated, and we can say this because of two reasons.

1. The small $\partial^{18}O$ shift.
2. In the Giggenbach's Na/1000 - K/100 – $\sqrt{(Mg)}$ diagram the waters of Alalobeda and Dobi do not plot on the maturity line, but in the field of partial equilibration.

The TD-4 and the Alalobeda springs show 18-30% fractions of vapour, (referring to the Giggenbach's diagram, 1991, page 254).

The Alalobeda spring number 3, Lake Begadeloma and Lake Hayk indicate possible evaporation. It is difficult to determine the percentage of fractionation, because of the difficulty in modelling the surface evaporation processes in these areas.

Tritium is absent in the springs and lack of this isotope may indicate a residence time prior to 1950 in the reservoir.

There is no general agreement on the origin of the recharge for the Tendaho geothermal field, but there are two options for the recharge zone. The options are based on the altitude and the piezometric relation they are:

1. D'Amore et al. (1997) suggested that the recharge could be in the order of 2000-2500 m on the plateau by calculating $\partial^{18}O$ vs. altitude.
2. Panichi (1995) hypothesised the existence of a regional underground flow, which starts from the Lake District and, through the southern Afar, reaches the Tendaho graben. His hypothesis is based on the observation, that the $\partial^{18}O$ values become more positive from south to north in the Ethiopian waters and that of the direction of the ground water flow goes in the same direction, and the water chemistry, on a regional scale, changes from a predominantly bicarbonate composition to a predominantly sodium chloride type. Therefore he argues that there is a regional flow of waters from south to north, that progressively change their composition and are stored in geothermal reservoirs.

6 CONCLUSIONS AND RECOMMENDATION

After assessing the available amount of data and results the following conclusions are given:

1. The water type of the Tendaho geothermal field is dominantly Na-Cl, neutral to alkaline geothermal water.
2. The Alalobeda springs, that are part of the Tendaho geothermal system exhibit an average temperature of 199°C ± 35. This temperature is close to that observed in the deep well of the Tendaho geothermal wells. Examining the activity diagram of Figure 4 and considering the above result, it is possible to conclude that the temperature of Tendaho reservoir temperature is greater than 200 °C.
3. From the isotopic diagram given in Figure 5 it seems that waters from high lands of Desse to Debrebrhan recharging the Alalobeda and Dubti geothermal fields. In addition the two logical argument given by D`Amore et.al. And Panichi, increase the possibility of that the recharge area could be more than one and that should be defined.

Recommendation

In order to obtain a good assessment of the geothermal energy resources of the Tendaho geothermal system, it would be essential to have a systematical sampling for chemical and isotopic data. That of the Lakes district, from high and low lands of Ethiopia.

ACKNOWLEGMENT

I would like to express my deepest gratitude to my supervisor Dr. G. Gianelli.

I would like to thank the International Atomic Enegy Agency (IAEA) that sponsored my research work here in Itally. And the Ministry of Mines and Energy f Ethiopia for granting me a study leave during these period.

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