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GEOCHEMICAL, ASSESSMENT
OF THE NORTHERN TENDAHO RIFT, ETHIOPIA

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ABSTRACT

Geochemical data of the hydrothermal manifestation, deep wells and cold water points from the Northern Tendaho Rift, Ethiopia, have been examined and processed in order to have a better understanding of the geothermal system with respect to the nature of the fluids, their maturity, temperature and upflow zone. In the Dubti area, where three deep wells are drilled, the temperature distribution computed from gas compositions and steam fraction could be tied to flow paths of the deep fluid along a fault starting from an upflow zone which is anticipated to be around the three main fumaroles having an estimated reservoir temperature of about 300°C. A set of hydrothermal minerals including calcite, anhydrite, pyrite, wairakite, prehnite, Mg-chlorite, albite, epidotes and diopside is in thermodynamic equilibrium with the geothermal waters of the wells in Dubti and with the waters of hot springs in the Alalobeda hydrothermal area. The equilibration temperatures computed from water and gas compositions of the wells in Dubti are consistent with the measured values. For the Alalobeda area, a temperature of about 205°C seems the most reliable. The isotopic composition of carbon and He and the He-Ar-N_2 relationship confirm an original magmatic source for the gas. Based on the isotopic composition of waters from the wells and sampled at the Alalobeda hot springs, the origin of recharge water can be fixed at an elevation of approximately 2500 m in the Ethiopian plateau (Western Escarpment).

INTRODUCTION

Aquater S.p.A. (ENI Group) and the Ethiopian Institute of Geological Surveys (E.I.G.S.) jointly carried out a prefeasibility study at the Dubti and Alalobeda areas, Northern Tendaho Rift in Ethiopia (Fig 1) in 1979-80. This was followed by a feasibility study in the area of major interest, Dubti, between 1990 and 1995 (Aquater, 1996).

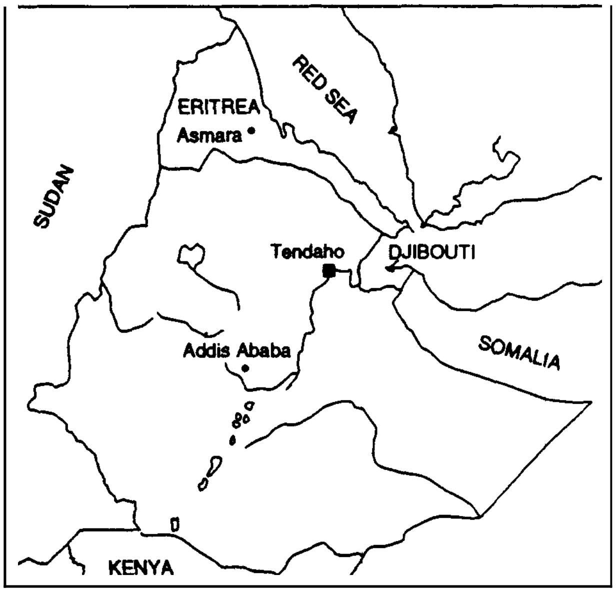

Fig. 1. Location of Tendaho Rift (Ethiopia).

In the Dubti plantation, the hydrothermal area extends for about 2 km^2 and presents isolated mud craters a few meters in diameter, minor fumaroles and steaming grounds which emit fluids formed prevalently by steam and minimum quantities of gases at the water boiling temperature. These manifestations are aligned along an active fault with SE-NW direction (Fig. 2).

The Alalobeda thermal area, 12 km SSW of Dubti, is characterized by the presence of hot springs with temperatures near the boiling point, fumaroles and steaming grounds, aligned on the eastern border of the graben which corresponds to a major fault. The hot springs extend for approximately 1 km toward N-NW, but the steaming grounds and gas emissions continue for about 3 km.

Some hot springs are also present near the Bagalodoma Crater Lake, approximately 22 km NNE of Dubti, with temperatures close to 50°C.

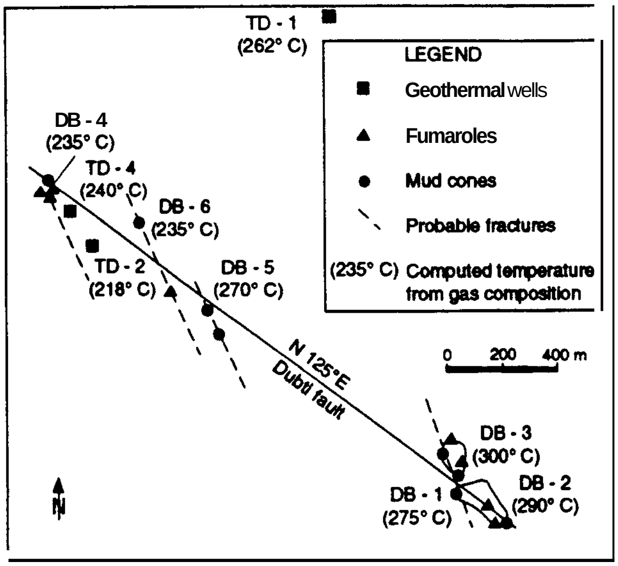

Fig. 2. Dubti geothermal area: location of geothermal wells and surface marufestations.

During the Tendaho Geothermal Project, 4 deep wells were drilled in the Dubti area (from 1993 to 1995):

- TD-1 well is characterized by very low flow rate and hence has no industrial interest. The measured temperature is about 270°C and production levels are at 850-900 m and 1190-1265 m.
- TD-2 well, which discharges at the average flow rate of 13 kg/s from a permeable level at 890 m has a measured temperature of about 220°C.
- TD-3 well, an unproductive well, with the casing shoe set at 830 m has a maximum measured temperature of 198°C.
- TD-4 well, a productive well, which discharges brine at about 70 kg/s, having a depth of about 250 m and a measured temperature of 216°C.

WATER CHEMISTRY

In the investigated area waters have been *studied* from the following points:

1. waters discharged from wells TD-1, TD-2 and TD-4 (collected at weirbox);
2. waters from the hot springs of Alalobeda;
3. waters from the thermal gradient boreholes;
4. fresh waters from wells used for domestic purposes and springs.

Table 1 lists selected chemical analyses data for the well samples from the weirbox, and the water composition for Alalobeda springs. The chemical composition of cold springs, wells used for domestic purposes and of the thermal gradient boreholes in the Dubti area are not reported in the Tables.

The degree of mineralization of the water from all three wells is similar. After the flash in atmospheric conditions, this level was recorded as 2.25 and 2.33 g/l for the TD-2 and TD4 productive wells respectively. In well TD-1 the water at bottomhole has a salinity of 2.10 g/l.

CLASSIFICATION OF WATERS

In chemical terms, the waters are similar in all three wells in the Dubti area. They are essentially sodium chloride waters with a fairly high sulphate content and very low Ca and Mg content. The $Cl\text{-}SO_4\text{-}HCO_3$ and Na-K-Mg diagrams (Giggenbach, 1988) were used for the chemical classification.

The anionic compositions of the waters from wells TD-1, TD-2 and TD-4 fall under the $Cl\text{-}SO_4\text{-}HCO_3$ diagram (Fig. 3) near the area that corresponds to normal geothermal fluids. Notwithstanding this, a considerable quantity of sulphates is evident, such that the mineral anhydrite phase can be considered always present in equilibrium or in oversaturation in all samples at the reservoir temperature. This high quantity of sulphates could be generated by the circulation of relatively deep recharge waters inside the large sedimentary surface sequence. In particular, in well TD-4 the production layer is located in the sediments and we cannot exclude that these sediments could also exist in deep zones of the reservoir which recharge the other wells. The highest sulphate values were found in the Alalobeda hot springs. The local shallow waters are located close to the bicarbonate corner, as they are highly diluted Na-

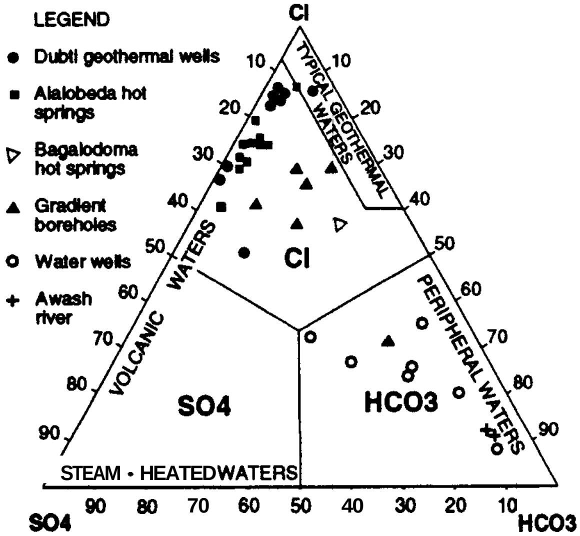

Fig. 3. Relative Cl, SO_4 and HCO_3 contents of waters on weght (mg/kg) basis.

HCO_3 waters. The waters of the gradient boreholes have high contents of Cl and SO_4 and they are located between the two end-members.

The Na-K-Mg triangular diagram (Fig. 4) is essentially based on the temperature dependence of equilibria among the minerals K-feldspar, mica, chlorite and the three cations Na^+, K^+ and Mg^{2+}. This diagram can also be used to classify waters as fully equilibrated with rock at given temperatures, partially equilibrated or immature as shown in the diagram of Fig. 4, which reports the data of wells TD-1, TD-2 and TD-4 and of all the other waters. From a geothermal point of view all samples collected in the wells are mature waters in full equilibrium. The temperatures of the wells indicated in the diagram are as follows: 240°C for TD-1 (sample of 14.06.94); 235" and 230°C for TD-2 (samples of 09.05.95 and 24.06.94); **252°**, 270' and 240°C for TD-4 (samples of 19.05.95, 25.05.95 and 04.06.95).

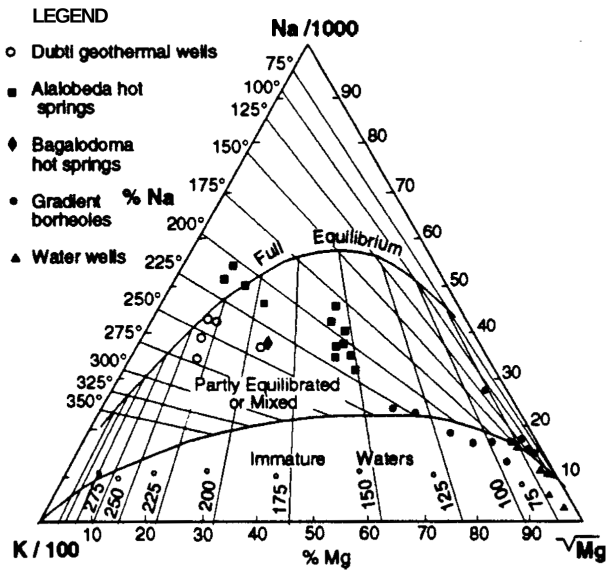

Fig. 4. Evaluation of Na-K-Mg temperatures.

For well TD-1, the temperature obtained from this diagram is lower than the measured minimum temperature by an average of 25°. This can be attributed to the relatively high quantity of magnesium. Moreover the muscovite used in the model has not been observed during the petrographic *study.* In well TD-2, the temperatures determined with the Na-K-Mg diagram are 10°C higher than the measured temperatures. In well TD-4 the temperatures in the diagram are much higher than those measured.

Although the geothermometric results are not entirely consistent with those of the saturation index method (see next section), and with the measured temperatures, the overall results suggest that the fluids from the wells and Alalobeda springs are in full equilibrium with the host rock (with a temperature of about 215°C for Alalobeda) Moreover it appears that strong mixing phenomena do not occur in the Dubti reservoir waters.

The cold waters of shallow wells are of sodium bicarbonate type. The waters of gradient boreholes are mainly of sodium chloride-sulphate type, rich in Na and Mg, with a maximum temperature close to 50°C. In the diagram of Fig. 3, they are intermediate between the shallow bicarbonate waters and the Alalobeda spring waters. The Same applies for the Bagalodoma immature waters. Considering the position of the points in the Na-K-Mg diagram (Fig. 4), a trend from diluted Na-HCO_3 waters to Na-Cl-SO_4 mature waters appears evident, where the SO, content is probably a function of the time of circulation in the upper sediments.

WATER GEOTHERMOMETRY

Several empirical cation geothermometers and those based upon silica concentrations have been applied to the waters of wells TD-1, TD-2, TD-4 and of the Alalobeda springs. The results are listed in Table 2. The geothermometers based on Li content have been disregarded, because they provide unrealistically low temperature values for all the waters.

The application of geothermometry based on silica concentration led to the following considerations:

-TD-1 well, whose fluid flow from bottomhole to wellhead is very limited but is continuous and relatively fast, shows a computed temperature ranging from 270' to 280°C which is consistent with the temperature measured in the aquifer.

-The temperature computed for TD-2 well falls between 220" and **225°C**, as that of the measured one in the aquifer.

-In well TD-4 the temperature computed using silica is **225°C**, approximately 8°C higher than that measured in the production layer at 250 m.

As regards the cation geothermometers, the following observations can be made:

-For TD-1 well, no cation geothermometer provides a temperature reasonably close to that computed using silica and to the measured temperature; the computed temperatures are always very low.

-In well TD-2, the application of geothermometers generally provided temperatures close to the measured value, i.e. approximately 220°C.

-In well TD-4, for the analysis performed on 25.05 95, the cation geothermometer provided a temperature much higher than the measured temperature. For the other two analyses the computed temperatures are close to the value produced from the silica content (Table **2**). The mean temperature obtained by applying all the cation geothermometers to the waters of well **TD-4** is in the range of **234°C±18°**. Such value, showing a high standard deviation, is considerably higher than the temperature measured in the local reservoir at **250** m, that is **216°C±2°**. This could mean that the fluid carries imprints of a reservoir zone hotter than that observed at shallow productive layers.

Taking into consideration all the geothermometers, the maximum temperature computed at **Alalobeda** with the **1990** compositions is **212°C** for the **AL-1** spring using the Na-K geothermometer (Giggenbach, **1988**), and **229°C** using the quartz geothermometer, no-steam loss (Fournier, **1983**).

SATURATION INDEXES

For a better understanding of water compositions for the main species, the method based on the saturation indexes of selected mineral phases was applied. The WATCH computer code (Amorsson, **1982**) at selected reservoir temperatures defines the composition and speciation of the reservoir water and the activity of the various species. The code also enables calculation of the activity products for several minerals. The saturation index SI for each mineral is the logarithm value of the ratio between the activity product and the equilibrium constant.

When examining the equilibria of hydrolysis reactions of alumo-silicates, the concentration of monomeric aluminium species must be known. In our case the monomeric aluminium content was not available. In order to make up for the lack of this parameter we assumed the existence of a mineral in equilibrium with the other alumosilicates. The use of this equilibrium between the selected phase and an alumosilicate is to stechiometrically balance for aluminium in a hydrolysis reaction. In our case we chose the microcline phase.

Table **3** shows the hydrolysis reactions considered in this paper. The following mineral phases reached saturation conditions at reasonable temperatures and thus they were used to calculate the equilibrium temperature: calcite, anhydrite, quartz, wairakite, prehnite, Mg-chlorite, albite, epidote, zoisite and diopside. As an example, Figure **5** shows the **SI** values calculated towards selected temperatures (between **160** to **260°C**) for the sample collected on **19.05.95** in well **TD-4.** We must consider that the SI values have a theoretical limit whch is essentially due to some uncertainties both in the analytical composition and in the mineral hydrolysis constants values. Therefore, the equilibrium temperature can be considered achieved for values of SI = 0 ± 0.25.

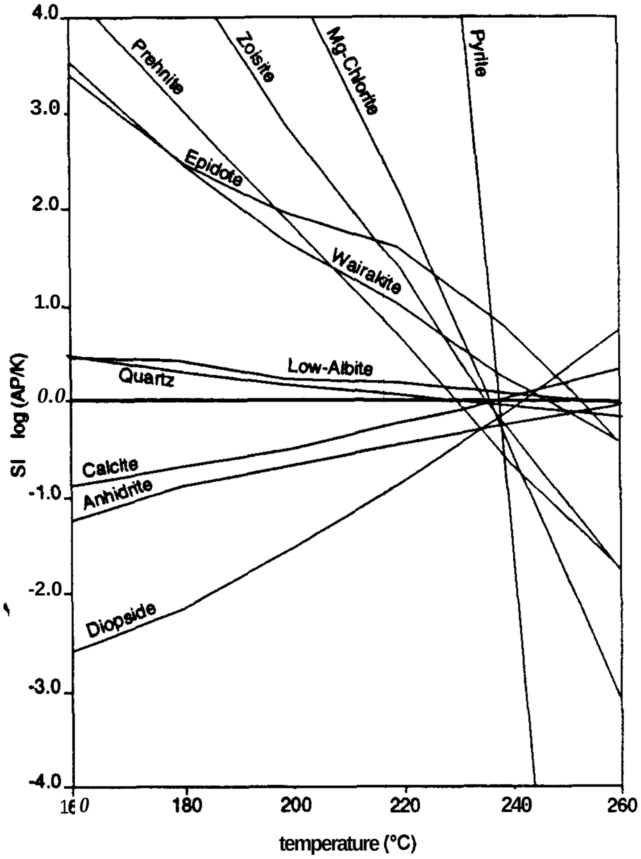

Fig. **5**. Saturation index vs temperature for sample collected on May **19, 1995** in well **TD-4.**

The results of the saturation index method applied to the waters from the Dubti wells may be summarized as follows:

-In well **TD-1,** the method was applied to the **14.06.94** sample, considered as the most representative because of sampling conditions. It corresponds to fluid discharged from the well after approximately 30 days of production at a flow-rate of a few litres per minute, thus avoiding flashing. The deep water composition was reconstructed by taking into consideration degassing effects and provided a temperature of **269°C±14°**, consistent with that measured in the well's production level.

-In well **TD-2** the average temperature calculated using the same minerals is **227°C±9°** for the **1995** sample and **228°C±8°** for the **1994** sample.

-In well **TD-4,** if all calculated equilibration temperatures are used for the three available analyses, an average value of **237°C±11°** is obtained.

This value is very close to that obtained from the application of cation geothermometers.

On applying this method to well TD4, the computed reservoir temperature is about 20°C higher than those measured at 250 m in the production zone. We can assume that the fluid originates from a deeper reservoir and that, through a local fracture, it could penetrate in the TD4 productive level, having a temperature of about 220°C. The 250 m production level, whch is hydraulically connected with the surface, is characterized by a temperature corresponding to the boiling-point-per-depth curve. Therefore it is possible to conclude that the fluid temperature decreases during its passage from the reservoir to the feed zone while the water composition still carries imprints of higher enthalpy conditions, as shown in the SI computation. The only exception to this is silica whose kinetic reaction allows rapid equilibration (225°C).

The method of saturation indexes was applied to samples from the Alalobeda springs AL-1 and AL-2 of the 1995 samples. The computed equilibration temperatures for AL-1 and AL-2 are 217°C± 17' and 204°C±17°, respectively.

WATER [illegible]IC [illegible]SITIC

Tab[illegible] 1 reports t[illegible] ti[illegible] data for $\delta^{18}O‰$, $\delta^{2}H‰$ ([illegible] SMOW) for the waters from the wells, after correction for steam separation at the atmospheric [illegible] and of the Alalobeda [illegible]ig[illegible] No tritium was detected in the study area. [illegible] isotopic composition [illegible] all water samples is reported in the δ^{2} [illegible] vs. δ^{18} [illegible] plot (F[illegible] 6). We note [illegible]ry i[illegible] compositions between springs AL-1 and [illegible] and wells TD[illegible] and TD[illegible] 1 The graphic [illegible]ti[illegible] for [illegible] [illegible]ater shows a clear shift of ^{18}O as in the deep [illegible]s in Dubti. [illegible] to [illegible] rock interaction processes in a hydrothermal environment. In the waters [illegible] minor p[illegible] ([illegible] AL[illegible] and AL-4), the ^{2}H and ^{18}C contents indicate possible evaporation. Wi[illegible]h an isotopic composition similar to th[illegible] of [illegible]ll TD[illegible] and TD-4, the [illegible]lal[illegible] [illegible]l waters are very lik[illegible] connected to a reservoir linked to [illegible] circuits similar to those present at Dubti.

In order to determine the isotopic composition of surface waters and fresh groundwaters (rivers, springs and wells), in 1994 Aquater and the E.I.G.S carried out a water sampling program over an area extending from Aysa'ita to the western plateau between Senbete and Maychew (Fig. 6). One of the objectives of the survey was to identify a possible area of recharge for geothermal waters of the Northern Tendaho Rift. The following relationship

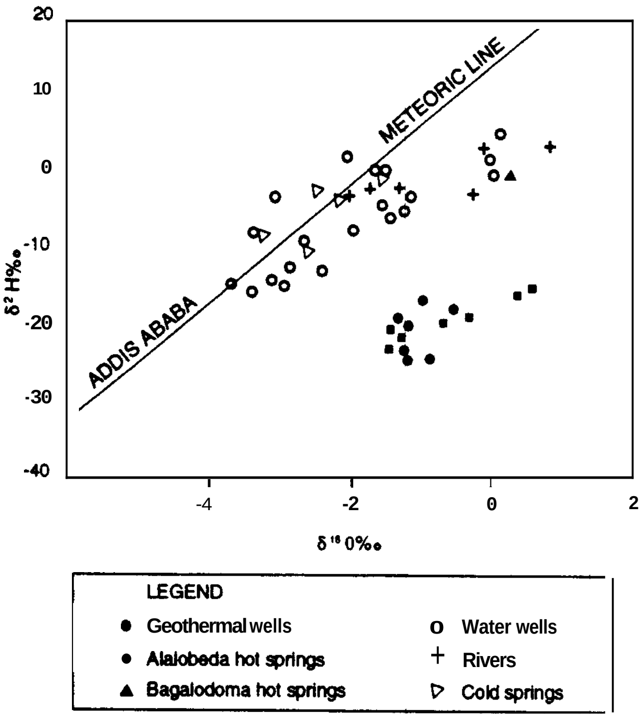

Fig. 6. Stable isotope water composition.

has been obtained for $\delta^{18}O‰$ vs. altitude (h) in meters above sea level:

$$h = 680 - 503\,\delta^{18}O‰$$

with $r^2=0.68$. The average $\delta^{18}O$ value, when inserted in the equation, produces an elevation of the recharge in the order of 2000-2500 m on the plateau. This information and the lack of tritium suggest that residence times could be in the order of several hundreds of years. The ^{14}C of carbonates determined in the TD-2 well waters, indicated that the water is younger than 7000 years (^{14}C = 43 AMS for the Qssolved carbonate).

GAS CHEMISTRY

The content of non-condensable gases in the wells is in the order of 16 mmoles/100 moles. Selected gas compositions of the wells and those of the Dubti and Alalobeda manifestations are listed in Table 4.

The gas compositions vary considerably in time and in space. This variability is pointed out in the triangular diagram of Fig. 7, which includes the following components: CH_4, $CO_2/50$ and the most reactive species ($H_2S+H_2+CO*10^4/2$). An alignment of the samples from the comer of the reactive species towards a high CH_4 content can be seen (Fig. 7). In the Dubti area, the mamfestations DB-1, DB-2 and DB-3 present the highest content of the reactive gases, particularly H_2S. In the alignment of active mamfestations, these are the must southeastern ones, as shown in Fig. 2. DB-4 and DB-6 marufestations

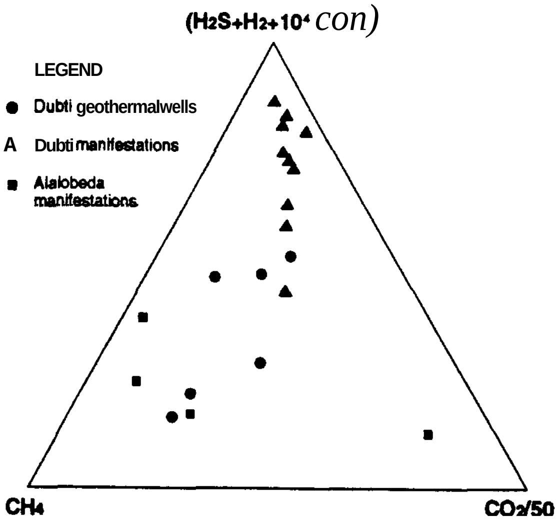

Fig. 7. $CH_4/CO_2/(H_2S+H_2+CO)$ diagram.

are the most northwestern ones along the alignment and show a composition similar to that of well TD-4. Well TD-2 presents a composition similar to that of Alalobeda.

Alalobeda gases differ from those of Dubti because of their lower H_2 and CO content. They appear as residual gases after *steam* losses. Alalobeda samples present the lowest reactive gases concentration in the area. AL-6 and AL-7 samples are the closest to the CH_4 end member together with well TD-2 (Fig. 7).

In Fig. 8 the relative compositions of N_2, Ar and He are plotted on a triangular diagram (Giggenbach, 1988). All manifestations in the Dubti area are contaminated by air. The origin of this air could be due to the fact that the collected *gas* is enriched in air dissolved in the condensate which is locally present in the sampled pools. If all the data are taken into consideration we observe a trend which has air or air-saturated water as one end member and a mixture of N_2 and He on the other end. In the graphic alignment, the wells are generally located closer to the He end member. This end member can be identified as the He of magmatic origin, particularly that of the mantle. This is confirmed by the $^3He/^4He$ ratios of wells TD-2 and TD-4 and of manifestations DB-3 and DB-6. The average value corrected for air contamination is $R/R_a = 13$. This value is slightly higher than that of typical ocean basalts coming from Mid *Ocean* Ridges, and therefore suggest the development of a plume originating from the lower mantle (hot spot type, like in Hawaii). These results are consistent with data obtained in the Djibouti lavas which show isotopic He ratios between 8 Ra and 15 Ra (comm. B. Marty, 1995 - Centre National de la Recherche Scientifique, Vandouevre de Nancy, France). The absolute values of $\delta^{13}C$ of CO_2 for wells TD-1 and TD-2 and of the Dubti and Alalobeda manifestations range from -3 to -6 per mil vs PDB (Table 4). These values are consistent with a prevailing component of deep magmatic origin. This component is even more abundant in the gases associated with waters produced by well TD-1 (-6 to -7) and confirm a minor sedimentary contribution from metamorphic reactions ($\delta^{13}C$ close to 0 per mil). The values of $\delta^{13}C$ of *Alalobeda* are between -4.5 and -6 5

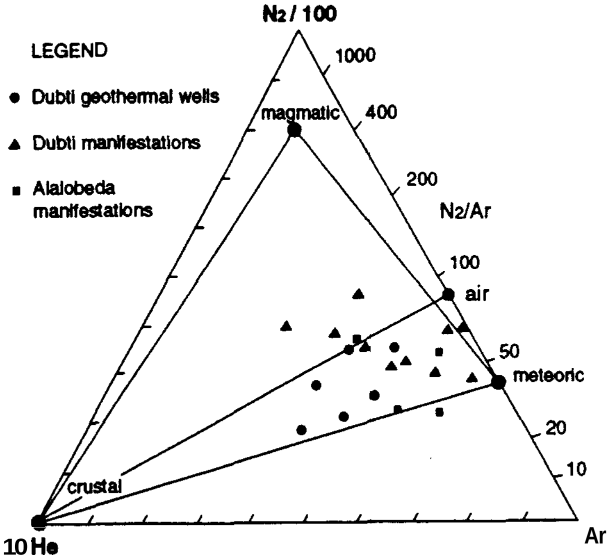

Fig. 8. Relative N_2, He and Ar contents in geothermal gas discharges on molal (volume) basis.

GAS EQUILIBRIA

Carbon monoxide is considered to be in chemical equilibrium with other "carbon" species such as CO_2 and CH_4 (e.g. Beratrami et al., 1985; D'Amore et al., 1987; Giggenbach, 1987; Chiodini and Cioni, 1989; D'Amore, 1991).

One way to calculate the temperature, and at the Same time check the equilibrium conditions in a vapour or liquid phase, is to we the logarithmic diagram by Giggenbach (1987), reporting on the axes $\log(CH_4/CO_2)$ vs $\log(CO/CO_2)$, as in Fig. 9 (method A). The positions corresponding to the gaseous compositions are the following:

-Wells TD-2 and TD-4 are in a temperature range between 200 and 240°C in a liquid phase.

-Well TD-1 shows a temperature of about 260°C in a liquid phase;

-The Dubti manifestations lie between 250" and 300°C with a highly variable steam content. Taking into consideration the results from the Dubti fumaroles referring to 1990 and 1995, we note that

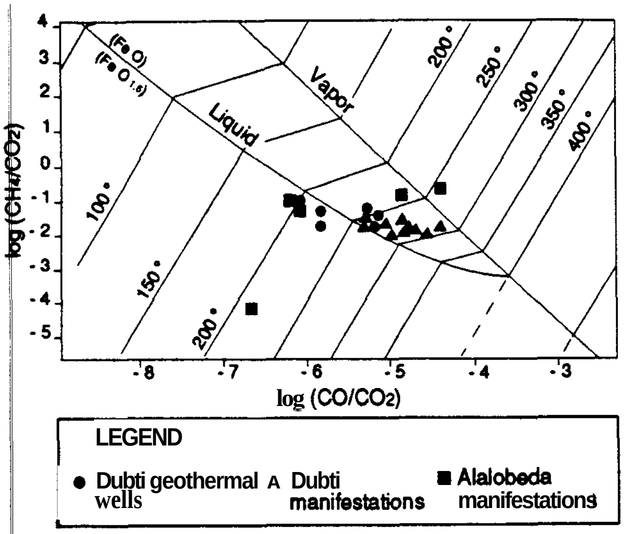

Fig. 9. Calculation of equilibrium temperatures using method A.

mamfestations DB-1 and DB-2 show temperatures close to 300°C. while madestations DB-4 and **DB-6** show temperatures in the range of 250°-260°C. In 1990 manifestations DB-1, DB-2 and DB-3 showed a high quantity of vapour in the examined equilibrium. **-Alalobeda** points are consistent with a temperature between 200° and 250°C.

When relatively **high** contents of H_2S are measured in fumaroles and wells in the *dry gas*, **as** in our case, it is then possible to use the method described by DAmore et al. (1987) and **by** Saracco and DAmore (1989) to compute the following parameters *of* the geothermal reservoir: temperature, in-place steam fraction "y" and $P(CO_2)$ (method B). Hence the three chemical reactions used are:

$$CH_4 + 2H_2O = CO_2 + 4H_2$$
$$CH_4 + 3CO_2 = 4CO + 2H_2O$$
$$H_2 + 3/2FeS_2 + 2H_2O = 3H_2S + 1/2F_3O_4$$

The following simplified expressions link the gas concentrations to the reservoir parameters temperature (T°K), **steam** fraction (y), partial pressure of CQ:

$$\begin{aligned} HC &= 4\log(H_2/CO_2) - \log(CH_2/CO_2) = \\ &\quad f1(T) + f1(y,B_i) - 4\log P(CO_2) \\ SHC &= 3\log(H_2S/CO_2) - \log(H_2/CO_2) = \\ &\quad f2(T) + f2(y, B_i) - 2\log P(CO_2) \\ COC &= 4\log(CO/CO_2) - \log(CH_4/CO_2) = \\ &\quad f3(T) + f3(y,B_i) \end{aligned}$$

B_i indicates the vapour/liquid distribution coefficient, known function of temperature for each species considered in the chemical reactions (D'Amore and Truesdell, 1988). The HC, SHC and COC are the known terms of the equations. The non-linear equation system is solved using a numerical approach.

The application of this method produced the results shown in Tab. 5. The hottest **well** is TD-1, with a temperature of 262°C, and the coldest well is TD-2, with a temperature of 218°C. Well TD-4 is in **an** intermediate position with a temperature of 240°C. This is much htgher than the temperature measured *at* the production level. In well TD-4, therefore, both gases and waters carry imprints of major enthalpy conditions, regardless of the discharge temperatures. *On* the contrary, in wells TD-1 and TD-2, the temperatures calculated from gases and waters confirm those measured in the local reservoir.

The values of "y" computed for the three wells indicate that a pure liquid phase occurs in the reservoir with no excess vapour. Therefore, the Dubti geothermal system is characterized **by** a typical water-dominated system *at* starting production conditions. The Alalobeda springs present negative values *of* steam fraction "y" and indicate that the produced fluid was degassed before reaching the surface.

The CO_2 pressures vary substantially in the present system, and were estimated in: 1.3 MPa in TD-1; 0.22 and 0.48 MPa in TD-2 respectively for samples collected in 1994 and 1995; 0.4±0.1 MPa (average value) in TD-4; 0.8-0.1 MPa in Alalobeda.

Dubti *gas* manifestations present an areal temperature gradient. DB-1, DB-2 and DB-3, in the south-east zone of the fault, present maximum temperatures (275°-300°C). DB-5 shows a value close to 270°C. DB-4 and DB-6, in the north-west portion and close to wells TD-2 and TD-4, present a value of 235°C.

GAS ISOTOPIC GEOTHERMOMETRY

The available gas isotopic compositions for the wells, the Dubti gas manifestations and the **Alalobeda** springs are reported in Table 4. The isotopic compositions **that** enable the calculation of temperatures from the δ^2H *of* the pair CH_4-H_2 are available only for wells TD-1 and TD-2. For 6 samples the **data** needed to calculate temperature by the $\delta^{13}C$ *of* the pair CO_2-CH_4 are available. The temperature evaluation **was** limited only to the Dubti area. Using the pair CO_2-CH_4, the computed temperatures are 700°C for TD-1, 410°C for TD-2 and 460°C for TD-4. For the Dubti madestations, an average temperature in the range of 472°C±13° was obtained. These values are consistent with a strong magmatic component for CO_2. Unfortunately, for the CH_4-H_2 isotopic pair the isotopic composition of H_2 did not enable precise calculations due to the scarce amount of H_2 and low pressure in the samples. In well TD-2, taking into consideration only the results given by the major signal at the mass spectrometer, a temperature close to 250°C was calculated. This value is higher than the measured temperature and the value computed using gas-geothermometry (about 220°C). For well TD-1, the computed temperature value is 320°C, which is higher than the value measured at well bottom (270°C).

CONCLUSIONS

The geochemical study of fluids produced by the wells at Dubti and by the hydrothermal manifestations in the main geothermal areas of the Northern Tendaho Rift provides fundamental information on the fluid characteristics and thermodynamic conditions of the local deep reservoir.

-The water discharged from the wells in Dubti is of sodium chloride type. It is mature and has not been mixed with surface waters. The remarkable presence of sulphate could be attributed to circulation in sedimentary levels where the productive zone of TD-4 is situated. The waters of the Alalobeda hot springs have a similar chemical composition to that of the Dubti area, with higher sulphate content due to its increasing solubility as the reservoir temperature decreases to about 205°C.

-The content of total dissolved solids which lies between 2.1 and 2.3 g/kg is low. The gas fraction compared to total fluid is also very low. In particular, for well TD-4, the value of non condensable gases compared to total water is in the order of 16 mmoles/100 moles. These results are of some interest for industrial exploitation and suggest low environment impact.

-Reservoir equilibrium temperatures and the CO_2 partial pressure values computed for the Dubti wells from gas and water chemistry are: 260°-270°C and 1.3 MPa for TD-1; 220°-225°C and 0.35 MPa for TD-2; 235°-240°C and 0.4±0.1 MPa for TD-4. For wells TD-1 and TD-2 the computed equilibrium temperatures are close to those of the measured values. In well TD-4, however, they are about 20° above the measured value at the 250 m production level. Consequently it is assumed that the fluid originated from a deeper reservoir and ascends along the Dubti fault and recharges the productive level of the well. It should be underlined that at 450 m, the temperatures measured are similar to those calculated. These levels have a negligible permeability in the area of wells TD-2 and TD-1, but the presence of a nearby reservoir having a temperature of 235°-240°C cannot be ruled out.

-In the Dubti area, natural gaseous manifestations are aligned along an active fault for approximately 2 km in a SE-NW direction. If the computed temperature values from gas compositions are plotted on the major sampled manifestations (Fig. 2) and also considering the temperature values computed from gas and water chemistry for the three wells, we observe a trend with maximum values between 275° and 300°C. The maximum temperature corresponds to the group DB-1, DB-2 and DB-3 in the SE, and declines towards the NW. In wells TD-2 and TD-4 the calculated and measured temperatures are the same as that computed in DB-4, the last fumarole at NW with a temperature estimated in 235°C. This temperature distribution is probably in relation to the relative positions of the wells and manifestations with respect to a local upflow zone in the SE portion of the Dubti geothermal area. A heat source is assumed near the feed reservoir of manifestations DB-1, DB-2 and DB-3, that produces a single liquid phase fluid moving in a vertical direction along fault planes with initial temperatures in the order of 280° and 300°C. Once horizontal permeable formations are reached the fluid expands, producing isotherms that take on a volumetric mushroom shape. With respect to this upflow zone, two possible flow paths can be assumed along the manifestation fault (independent of well TD-1). In the first path, the fluid is assumed to rise towards the surface and simultaneously moves through a formation characterized by good permeability, gradually reaching at shallower levels and with decreasing temperatures, the area of TD-4 and of manifestation DB-4. The second flow path may be assumed at greater depths, in a reservoir zone with low permeability. Moving very slowly, the fluid would cool to a greater extent compared to the fluid closer to the surface which has a greater chance of mobility. Such fluid could feed the deeper levels of well TD-2.

-In the Dubti wells the values of the calculated in-place mass vapor fraction ("y") are close to zero. This, according to reservoir engineering information, confirms the existence of a liquid-dominated geothermal system. On the other hand, the manifestations present positive and significantly higher "y" values, generally between 2 and 10%. At point DB-6, the only sample taken during the last survey (1995), a y value approaching 1 was calculated. It is unlikely that these values refer to the fluid in the original reservoir, but rather to a local re-equilibration of gases in a two-phase system formed during its slow ascent towards the manifestations. In order to confirm this assumption it will be necessary to carry out periodic monitoring of the fluids, at least for the more important manifestations including detection of CO.

-For **Alalobeda,** gas geothermometry provides temperatures in the order of 240°C, higher than those calculated for the waters which were between 200" and 220°C, and much higher $P(CO_2)$ values than those calculated from the composition of waters. This could indicate that the real temperature of the original water is approximately 240°C. It then mixes with cold shallow old water and reaches temperatures of 200°-220°C. These shallow waters do not have a local origin, considering the observed isotopic compositions. Thus, the waters sampled at the Alalobeda springs could be of mixed origin.

-The isotopic composition indicates, however, that the cold mixing waters are characterized by an analogous circulation period, but with lower temperature. The isotopic composition of the reservoir water discharged by wells TD-1, TD-2 and TD-4 in the Dubti area and by the hot springs in Alalobeda, show a marked water rock interaction effect caused by temperature. This effect is much greater in well TD-1. The $\delta^{18}O$‰ values also show that recharge corresponds to feed elevations above 2000 m. This value is approximate given the scarcity of data to correlate meteoric precipitation and exact elevation. Nevertheless, it indicates that recharge of the Tendaho geothermal reservoirs originates in the upper part of the Ethiopian escarpment and/or in the plateau, and excludes local recharge. The absence of Tritium confirms a long residence time. However, the residence time of the water from the recharge area to the Tendaho geothermal field does not exceed 7000 years.

-The gases associated with the geothermal fluids of the Tendaho area indicate that CO_2, which is the prevailing species, has a strong component of magmatic origin. The supply of magmatic gases is confirmed by the relatively high He content (linked to a basaltic type) and by the $^3He/^4He$ ratio.

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Tab. 1 - Chemical composition of brines from Dubti wells at weirbox and from Alalobeda hot springs.

Well or Spring	pH	conductivity µS/cm at 20°C	HCO3+CO as CO2 mg/l	Cl mg/l	SO4 mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	SiO2 mg/l	H2S mg/l	NH4 mg/l	F mg/l	Li mg/l	Al mg/l	B mg/l	Fe mg/l	δO-18‰ vs SMOW	δD‰ vs SMOW
TD-1(*)	6.07	2754	177	747	38.4	8.2	0.10	462	51	640	4.2	33.9	1.3	0.65	0.12	5.1		-0.59	-17.3
TD-2	8.33	3372	12.3	874	161	14.6	0.018	690	68	459	2.2	1.41	1.1	0.80	0.45	4.0	0.04	-1.03	-16.1
TD-4	8.42	3135	17.6	881	124	7.8	0.028	685	75	477	1.7	1.47	0.9	1.06	0.60	4.7	0.06	-1.37	-18.9
AL-1	8.03	3271	14.1	766	244	31.2	0.008	682	46	306	4.0	1.17	0.7	0.54	0.20	2.6	0.01	-1.31	-21.0
AL-2	9.10	2470	34.5	724	205	9.5	0.020	505	38	342	6.1	1.01	0.8	0.39	0.20	1.5		-1.49	-20.1
AL-3	8.80	2520	36.1	653	240	10.1	0.10	520	40	327	3.2	1.14	0.7	0.40	0.22	1.0		-0.71	-19.1
AL-4	8.60	2620	35.2	767	230	9.8	0.050	540	41	337	3.4	0.57	0.8	0.42	0.06	0.4		0.54	-14.5
AL-5	7.50	2670	37.9	710	245	9.3	0.28	530	39	337	7.0	4.43	0.8	0.40	0.04	0.2		0.33	-15.3
AL-8	7.90	2950	16.7	773	230	32.5	0.011	647	49	320	3.4	1.12	0.6	0.45	0.16	2.6	0.03	-0.37	-18.3

(*) Sampled at the bleeding point.

Tab. 2 - Temperature values computed through the application of water geothermometers.

Well or Spring	Na-K (1) °C	Na-K (2) °C	Na-K (3) °C	Na-K (4) °C	Na-K (5) °C	Na-K (6) °C	Na-K (7) °C	Na-K-Ca (8) °C	K-Mg (9) °C	SiO2 (10) °C	SiO2 (11) °C	SiO2 (12) °C
TD-1	199	206	205	223	226	212	240	214	240	280		276
TD-2	189	196	196	216	218	204	233	211	227	216	220	
TD-4	200	208	207	224	227	213	241	225	229	219	222	
AL-1	150	155	159	187	186	174	203	181	228			211
AL-2	159	164	168	194	194	181	211	192	170			220
AL-3	161	167	170	195	195	183	212	193	157			216
AL-4	160	165	168	194	194	182	211	193	165			219
AL-5	157	162	166	192	192	179	209	192	147			219
AL-8	160	166	169	195	195	182	211	186	229			214

(1) Truesdell, 1976
(2) Tonani, 1980
(3) Arnorsson, 1983 (25°-250°C)
(4) Arnorsson, 1982 (250°-350°C)
(5) Fournier, 1983
(6) Nieva and Nieva, 1987
(7) Giggenbach, 1983
(8) Fournier and Truesdell, 1973
(9) Giggenbach, 1988
(10) Arnorsson, 1982
(11) Fournier, 1983 (maximum steam loss)
(12) Fournier, 1983 (no steam loss)

Tab. 3 - Equilibrium chemical reactions used to calculate the values of saturation indexes.

n.	Equilibrium chemical reactions
1	2 microcline + $6H_2O^-$ + Ca^{2+} = walrakite + $2K^+$ + $2H_4SiO_4$
2	2 microcline + $6H_2O$ + $2Ca^{2+}$ + $2OH^-$ = prehnite + $2K^+$ + $3H_4SiO_4$
3	3 microcline +$12H_2O$ + $2Ca^{2+}$ + OH^- = zoisite + $3K^+$ + $6H_4SiO_4$
4	2 microcline+$4H_2O$+$2Ca^{2+}$+$Fe(OH)_4^-$ +OH^- = epidote +$2K^+$+ $3H_4SiO_4$
5	microcline + $5Mg^{2+}$ + $8OH^-$ = Mg-chlorite + K^+ + $2H_2O$
6	microcline + Na^+ = albite + K^+
7	diopside + $4H^+$ + $2H_2O$ = Ca^{2+} + Mg^{2+} + $2H_4SiO_4$
8	8 pyrite + $26H_2O$ + $10OH^-$ = $8Fe(OH)_4^-$ + SO_4^{2-} + $15H_2S$
9	quartz + $2H_2O$ = H_4SiO_4
10	anhydrite = Ca^{2+} + SO_4^{2-}
11	calcite = Ca^{2+} + CO_3^{2-}

Tab. 4 - Dry gas compositions in moles % and gas isotope compositions of geothermal fluids in the northern Tendaho basin.

Well or Spring	H2S	CO2	N2	CH4	He x 10000	H2	Ar	CO x 10000	δC-13‰ CO2 vs PDB	δO-18‰ CO2 vs SMOW	δC-13‰ CH4 vs PDB	δD‰ CH4 vs SMOW	δD‰ H2 vs SMOW
TD-1	0.66	94.4	1.1	2.57	14	0.20	0.016	6.1	-6.13	-10.9	-11.5	-137	-390
TD-2	0.78	81.3	8.4	5.00	190	0.18	0.193	0.6	-4.05	-7.22	-20.7	-157	-350
TD-2	0.73	82.9	9.1	4.13	139	0.10	0.203	1.4	-3.40	-8.41	-22.9		
TD-4	0.67	83.7	10.4	1.26	30	0.26	0.161	4.6	-4.82	-7.59	-20.4		
DB-1	1.41	92.1	3.8	1.37	13	1.43	0.077	14.0	-4.14	-9.42			
DB-2	3.14	89.0	5.5	0.49	10	0.78	0.130	10.0					
DB-3	6.59	86.1	2.9	1.14	18	1.26	0.036	11.0	-3.66	-2.66	-18.8		
DB-4	0.42	87.9	3.7	1.54	33	0.18	0.026	4.0		-3.84	-7.33		
DB-5	1.80	87.1	4.6	0.97	130	0.48	0.024	9.5	-3.80	-3.25	-19.7		
DB-6	0.29	86.4	6.9	1.33	30	0.69	0.114	6.9					
AL-2	0.18	89.9	5.6	0.31	100	0.01	0.015	0.2	-4.79	-11.5			
AL-3										-6.49	-0.82		
AL-6	0.72	74.6	10.5	3.68	71	0.05	0.328	0.5					
AL-7	0.90	85.4	7.3	4.20	76	0.05	0.199	0.6					

Tab. 5 - Values of the reservoir parameters computed using method B.

Well or Spring	t °C	P(CO2) MPa	y
TD-1	262	1.30	0.0022
TD-2	215	0.22	-0.0003
TD-2	218	0.27	-0.0006
TD-4	240	0.32	0.0025
DB-1	266	0.33	0.09
DB-2	287	0.45	0.0105
DB-3	300	0.40	0.0025
DB-4	243	0.84	0.0035
DB-5	286	0.83	0.006
DB-6	235	0.33	0.9
AL-2	220	1.0	-0.002
AL-6	240	0.84	-0.008
AL-7	245	0.1	-0.02