Geochemical Characteristics of Thermal Springs in Volcanic Areas of Antsirabe-Itasy, Madagascar: Preliminary Results.

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Abstracts - There are several thermal springs in Madagascar for which a few locations are known, but for which there are not enough available temperature and chemical measurements. Two types of geothermal systems are recognized in this country: those driven by magmatic heat (magmatic systems) and those associated with high regional heat flow and active faulting (extensional systems). In volcanic areas of Antsirabe-Itasy, it is clear that many of the geothermal fields are related to volcanism and also controlled by fault zones.

Thermal springs in these volcanic areas offer the possibility of geothermal energy. Many of these sites are not so located and require evaluation before the geothermal potential of the areas can be assessed. In order to begin filling in data gaps, inter-comparison of data sets from previous analyses has been undertaken. Over 20 available chemical analyses were obtained from these springs with previously limited data.

There is not a considerable variation in the chemical composition of the springs. Fluids from volcanic area of Antsirabe (magmatic-associated system) have higher Na, K and Cl concentrations and have lower Mg and Ca concentrations compared to their extensional counterparts (magmatic area of Itasy). These differences are observed in spite of the fact pH and salinity ranges are broadly similar. CO_2 or HCO_3 always shows high concentration whereas SO_4 tends to increase.

A preliminary evaluation of temperatures indicates most of the sites have relatively low to medium geothermal potential. Temperatures of the reservoir at depth are estimated to be between 75°C-152°C and were calculated using chalcedony geothermometer. Some of the reservoir temperatures of these magmatic-associated systems appear promising and may support geothermal power plants.

Cold springs can also provide anomalous geothermometer temperatures indicating a geothermal resource, and that sampling of cold springs can be used as an exploration tool in areas with no surface expression of geothermal systems.

Further investigation based mainly on thermal gradient drilling, geophysical and geological explorations, remote sensing and geothermal GIS, is necessary to determine the geothermal resource potential of selected sites (resource assessment) and to help identify if they have commercial reservoirs (production wells, capacity, nature of the waters, depth and temperature of the reservoir).

Keywords: *Thermal springs, volcanism, geochemistry, geothermometry, Antsirabe-Itasy.*

Résumé - Il y a plusieurs sources thermiques à Madagascar dont quelques emplacements sont connus, mais il n'y a pas assez de mesures de températures et d'analyses chimiques disponibles. Deux types de systèmes géothermiques sont connus dans le pays: ce commandé par la chaleur magmatique (système magmatique) et ce associé avec le haut courant de chaleur régionale et avec les failles actives (système en extension). Dans les régions volcaniques d'Antsirabe et d'Itasy, il est clair que beaucoup des champs géothermiques sont en rapport avec le volcanisme et aussi contrôlés par des zones de failles.

Les sources thermiques dans ces régions volcaniques offrent la possibilité d'énergie géothermique. Beaucoup de ces sites ne sont pas bien localisés et exigent une étude préliminaire avant toute estimation et évaluation de la potentialité géothermique des régions.

Dans l'établissement des bases de données préliminaires, une comparaison entre l'ensemble des données d'analyses antérieures a été entreprise. Plus de 20 analyses chimiques disponibles ont été obtenues de ces sources avec des données limitées.

Il n'y a pas de variation considérable dans la composition chimique des sources. Les fluides de la région volcanique d'Antsirabe (système magmatique associé) montrent des concentrations élevées en Na, K et Cl mais des concentrations inférieures en Mg et en Ca, comparés à leurs équivalents de la région magmatique d'Itasy. Ces différences sont observées malgré le fait que le pH et les gammes de salinité sont grossièrement semblables. CO_2 ou HCO_3 montre toujours une haute concentration alors que SO_4 a tendance à augmenter.

Une évaluation préliminaire des températures indique que la plupart des sites ont relativement une potentiel géothermique faible à moyenne. Les températures des réservoirs en profondeur sont estimées entre 75°C-152°C et ont été calculées à partir du géothermomètre utilisant la chalcédoine. Quelques-unes des températures des réservoirs de ces systèmes magmatiques associés paraissent prometteuses et peuvent supporter des centrales électriques géothermiques.

Les sources froides peuvent fournir des températures anormales utiles en géothermomètre qui indiquent une ressource géothermique, et cet échantillonnage de sources froides peut être utilisé comme un outil dans l'exploration des régions sans manifestation superficielle de systèmes géothermiques.

Des investigations plus approfondies, basées principalement sur les gradients thermiques obtenus à partir des forages, sur l'exploration géophysique et géologique, sur la télédétection et le SIG géothermique, sont nécessaires pour déterminer la ressource géothermique potentielle des sites sélectionnés (estimation de la ressource) et aident ainsi à identifier si ils ont des réservoirs commerciaux (puits ou forage de production, capacité, nature des eaux, profondeur et température du réservoir).

Mots clés: *Sources thermales, volcanisme, géochimie, géothermométrie, Antsirabe-Itasy*

1. INTRODUCTION

There has been no detailed research on the geochemical characteristics of various Madagascar geothermal resources. However, there are many sites throughout the country that may have potential for utilization of geothermal resources, but for which insufficient information is publicly available to evaluate the individual resources.

The geothermal system in the Antsirabe-Itasy region has been termed magmatic geothermal, not because of magmatic fluids, but because of a magmatic heat source, and is associated with recent faulting in areas of thinned and extending crust (Fourno and Roussel, 1994).

The Itasy volcanic edifices all lie directly on the migmatite Precambrian basement, and there is – contrary to the Antsirabe area – no Miocene to Pliocene basalt underlying the Quaternary volcanic deposits (Besairie, 1959a and 1959b). Locations of known thermal springs are shown with the geological map in Figure 1.

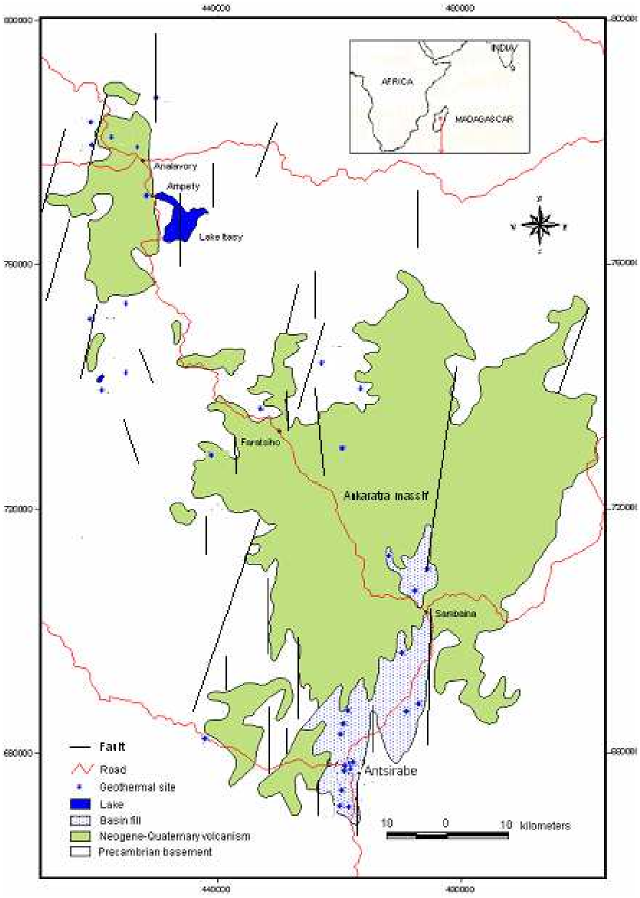

Figure 1: **Simplified geological map of the study area showing the known thermal springs (after Besairie, 1959a)**.

In this paper, the chemical analyses of thermal springs from the two volcanic areas were used to estimate subsurface temperatures in geothermal systems.

The purpose of this work is to fill in data gaps and these data will allow delineation of poorly characterized or understood geothermal areas that could be developed for electrical power generation or direct-use applications.

2. METHODS

A reconnaissance thermal spring exploration work was done from 1927 to 1968 and most of collected samples were analyzed by the Geological Survey of Madagascar (Tournier, 1926; Dufour and Jaegle, 1927; Brenon and Bussiere, 1959; Lenoble, 1946; Besairie, 1959a and 1959b; Joo’, 1968). Subsequent studies were carried out by VIRKIR Company (Gunnlaugsson et al, 1981).

All available chemical analysis of major element from the springs have been collected in these previous studies. A total of 23 chemical analyses: 21 hot springs, 2 cold springs were taken for this study. Inter-comparison of data sets has been undertaken. The data from the analyses of Itasy area were then compared to available water data from Antsirabe area.

Quartz, chalcedony, amorphous silica, and Na-K-Ca geothermometer calculations were performed. Chemical geothermometer calculations are empirical, but in most cases seem to give a reasonable estimate. Geothermometer equations used in this paper are from Henley et al (1984).

The data from these geothermometer calculations were then compared to available $\Delta^{18}O_{(SO4-H2O)}$ geothermometer data from a few sites in the region (Gunnlaugsson et al, 1981).

3. PRELIMINARY RESULTS

Some of the spring deposits of Antsirabe-Itasy field form a group of small springs and seeps. Others show travertine mound with a trace of siliceous sinter.

3.1 Water chemistry

The name of the springs is listed in Table 1, and the analytical results are summarized in Table 2. There is not a considerable variation in the chemical composition of the springs. Geochemical data for major ions in these waters show broadly similar silica content, about 53-176 mg/l. The pH values in the waters are between 6.52 and 8.21. Temperatures of the springs range from 18ºC to 58ºC.

The major element concentrations (Table 2) show that the Antsirabe area thermal waters tend to have Na concentrations approximately 10 times higher than Ca and K, with overall concentrations similar for nearly all the springs. Fluids from volcanic area of Antsirabe (magmatic-associated system) have broadly higher Na, K and Cl concentrations and have lower Mg and Ca concentrations compared to their extensional counterparts (magmatic area of Itasy). These differences are observed in spite of the fact pH and salinity ranges are broadly similar. CO_2 or HCO_3 always shows high concentration whereas SO_4 tends to increase, as seen in Table 2.

No.	Name of the springs
1*	Ranomafan I
2*	Ranomafan II
3	Ranomafan II
4*	Lac
5	Lac
6*	Hôpital
7	Hôpital
8*	Parc
9*	Ranovisy
10	Ranovisy
11*	Visikely
12*	Antsiravazokely
13	Antsira Andranotsara
14	Betafo ranomafana
15	Ramainandro
16	Sahasarotra
17	Soavinandriana Ranomafana
18	Masahona
19	Andranomangotraka
20	Amparaky
21	Marais d’Ifanja
22	Mahatsinjo
23	Anosibe Ranomafana

Table 1: List of the springs (samples from Gunnlaugsson et al, 1981; *samples from Geological Survey of Madagascar, 1946-1959).

No.	T(°C)	pH	SiO_2	Ca	Mg	K	Na	Cl	HCO_3 $+(CO_2)$	SO_4
1*	51	nd	142	111.0	72.1	279.0	1345	496.0	1613	197
2*	51	nd	160	179.0	80.0	258.0	1245	500.0	1710	194
3	51	7.56	133	94.4	nd	176.5	1389	478.0	2645	200
4*	35	nd	126	119.0	49.0	243.0	1143	421.0	1567	84
5	38.5	6.95	134	94.1	62.1	151.9	1264	437.0	2698	177
6*	42	nd	138	134.0	74.0	268.0	1316	489.0	1771	181
7	45	7.14	140	111.9	70.2	185.2	1399	481.0	2860	205
8*	26	nd	133	123.0	70.0	283.0	1262	479.0	1724	186
9*	42	nd	159	119.0	69.0	285.0	1342	496.0	1738	199
10	46	7.4	149	124.7	70.6	186.3	1424	486.0	2816	204
11*	27	nd	105	110.0	44.0	209.0	669	253.0	1052	75
12*	26	nd	134	167.0	5.0	99.0	962	385.0	414	137
13	18	5.95	91	26.9	17.5	11.3	20	1.5	450	2
14	58	8.21	69	18.5	1.7	5.3	123	7.2	111	162
15	42	6.52	53	94.3	30.0	73.5	919	166.9	1508	220
16	41	7.1	176	109.9	63.4	173.0	1118	516.5	2763	204
17	45	6.91	128	236.3	234.7	31.5	260	59.2	1493	557
18	57	6.87	133	135.3	70.2	40.7	586	35.4	1016	908
19	28	6.72	124	491.1	418.9	56.3	649	523.0	3634	369
20	24	6.54	74	277.9	159.7	27.9	225	151.0	1732	104
21	46	6.98	107	208.5	202.2	22.5	352	77.5	1152	940
22	40	6.79	98	205.8	7.7	18.3	393	57.6	715	942
23	49	6.79	81	216.9	8.2	21.3	400	97.2	720	923

Table 2 : The chemical compositions of waters from the Antsirabe-Itasy region. Concentrations are in ppm; nd: not determined (data from Gunnlaugsson et al, 1981; *data from Geological Survey of Madagascar, 1946-1959).

The $Cl-SO_4-CO_2+HCO_3$ triangular plot (Figure 2) is used for an initial classification of geothermal water samples (Giggenbach, 1988; Giggenbach and Goguel, 1989). The chemical composition of the waters is investigated in terms of relative Cl^-, SO_4^{2-} and $CO^{2-}+HCO^{3-}$ concentrations (Figure 2), and relative Na+K, Ca and Mg concentrations (Figure 3).

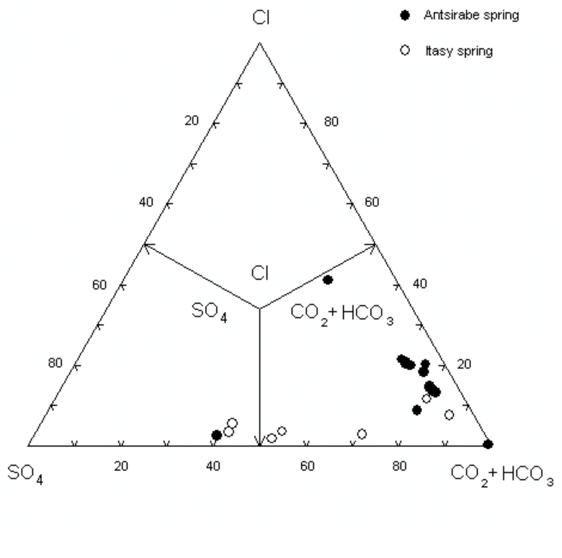

Figure 2: Relative Cl, SO_4 and CO_2+HCO_3 contents of the Antsirabe-Itasy thermal waters on weight (mg/kg) basis. Fields from Giggenbach (1988).

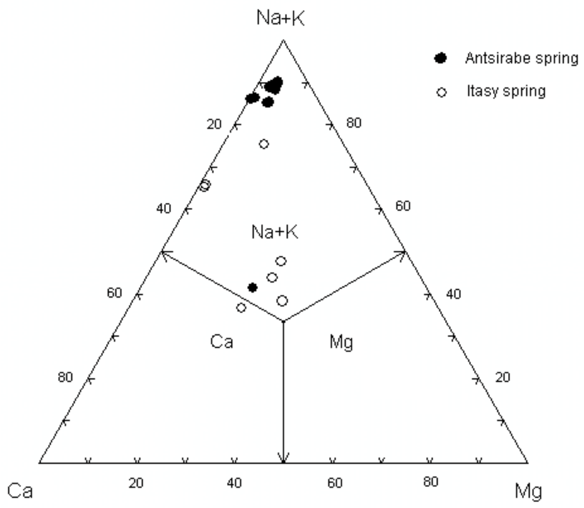

Figure 3: Relative Na+K, Ca and Mg concentrations.

An inspection of these plots points out the existence of two types of water: The first type is Na-carbonate water and includes the majority of the springs in the Antsirabe geothermal field; whereas most of the springs in the Itasy area are bicarbonate water. This group includes also two cold-water samples (sample No. 13 and No.20). The second type is sulfate water and includes samples No. 14, 22 and 23. It is shown that water of sample No.12 plot between CO_2+HCO_3 and Cl fields yielding a mixing along the line between peripheral and mature water fields, but it never attains maturity.

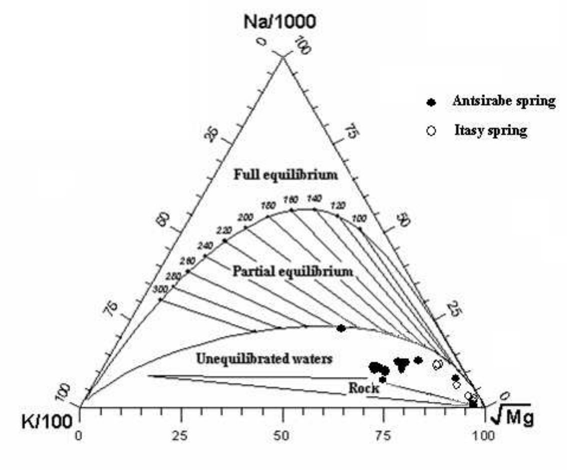

Figure 4: Na-K-Mg1/2 triangular diagram of thermal spring waters in the Antsirabe-Itasy region (Giggenbach, 1988).

All the data points are plotted in the Na-K- $Mg^{1/2}$ triangular diagram (Figure 4) (Giggenbach, 1988). None of the Antsirabe-Itasy waters attains a water-rock chemical equilibrium; so, they are are unequilibrated ones (immature waters). Only sample No.12 (chlorure-carbonate water) indicates attainment of partial equilibrium (mature waters area), whereas other CO_2-rich waters and SO_4-rich waters are situated close to the $Mg^{1/2}$ vertex. These “immature waters” provide unreliable Na-K-Ca temperatures.

3.2 Geothermometry

Calculated geothermometer temperatures (°C) are shown in Table 3.

Table 3: Estimated temperature of geothermal reservoir for the Antsirabe-Itasy thermal waters (Temperature in ºC, nd: not determined).

No.	$T_{Na\text{-}K\text{-}Ca}$	T_{quartz}	$T_{amorphous\ silica}$	$T_{calcedony}$	$T\ \Delta^{18}O_{(SO4\text{-}H2O)}$
1*	252	158	36	134	nd
2*	244	165	42	142	nd
3	221	154	32	129	nd
4*	249	151	29	125	nd
5	215	154	32	129	nd
6*	248	156	34	132	nd
7	222	157	35	132	137
8*	255	154	32	129	nd
9*	253	165	42	142	nd
10	220	161	38	137	nd
11*	265	140	19	114	nd
12*	195	154	32	130	nd
13	240	132	12	105	nd
14	135	117	-1	88	nd
15	185	104	-12	75	nd
16	227	171	48	149	140
17	176	151	30	126	129
18	166	154	32	129	nd
19	169	149	28	124	149
20	174	121	2	92	152
21	151	141	20	115	nd
22	138	136	16	109	nd
23	144	126	7	98	nd

The purpose of a geothermometer is to estimate the temperature at depth, given concentrations of dissolved substances at the surface. This method assumes that concentrations at depth are preserved as the waters flow to the surface, and measures the degree to which the substances were in equilibrium at depth. Geothermometer equations used in this paper are from Henley et al (1984).

Calculated temperatures values in Table 3 show notable disagreement, which may affect the applicability of the chemical geothermometers to the Antsirabe-Itasy system. Based on these analyses, Na-K-Ca, quartz, and chalcedony geothermometers indicated temperatures in the range of 75 to 255°C.

The quartz geothermometer values (from 104 to 171ºC) are below the accepted >180ºC temperature range (Table 3). Therefore, the waters likely would not have been in equilibrium with quartz, rendering these values unreliable, and thus they are not considered useable.

Compared with quartz geothermometer, the chalcedony geothermometer display relatively lower reservoir temperatures between 75 and 149ºC. Since chalcedony, rather than quartz, controls silica saturation at temperatures less than 180ºC (Fournier, 1991), it appears that the chalcedony geothermometers better reflect the reservoir temperatures for the Antsirabe-Itasy field, but this is further checked with cation geothermometers. If the chalcedony temperature values are not in the accepted 140-180ºC temperature range for this geothermometer, they are also unlikely to be accurate. But the values from Ranomafana II site No.2 (142°C), Ranovisy site No.9 (142°C) and Sahasarotra site No.16 (149°C) are reliable, hence, they are considered useable.

The negative temperatures given by the amorphous silica geothermometer are clearly incorrect. Since the <140ºC temperature range corresponds to the amorphous silica geothermometer, the amorphous silica geothermometer equation was considered. Because most of surface temperatures of thermal springs (in the range 26 to 58°C) are lower than those of calculated by the amorphous silica geothermometer considered as in equilibrium at depth, this method may not be applicable.

For all springs, the Na-K-Ca geothermometer calculations show globally elevated temperature (more than 200°C) and indicate a higher temperature than the silica geothermometers (Table 3). This method assumes that the water contains dissolved elements in equilibrium with aluminosilicate minerals such as feldspars that contain Na, K and Ca (Fourrier and Truesdell, 1973). Thermal waters have relatively higher amounts of Na and K, two elements which would be produced from dissolution of volcanic glasses which are common in the studied areas. However, there are other sources of these elements; in particular, clay in the sedimentary basin fill material in the Antsirabe area (Lenoble, 1946). Then, since the samples were collected in close proximity to a salt flat, the concentrations of Na, K, and Ca are likely to be unreliably high. Thus, the Na, K and Ca content of water springs in the studied area have elevated sulfate content compared to other geothermal systems worldwide (Garchar and Arehart, 2008). Therefore, even though the temperature values from the Na-K-Ca geothermometer appear promising, they are not likely to truly reflect the reservoir temperatures because the water is salty.

In most of the sites, the temperatures values given by the $\Delta^{18}O_{(SO4\text{-}H2O)}$ geothermometer (Gunnlaugsson et al, 1981) of the compared samples from previous analyses never showed significant change (129-152°C). Temperatures values from $\Delta^{18}O_{(SO4\text{-}H2O)}$ geothermometer correspond relatively well to calculated chalcedony geothermometer. Globally, it is unlikely that the oxygen-18 of the water could conceivably be affected by rock-water interaction (Garchar and Arehart, 2008). There is also no significant evaporate or salt in the studied region. So, the sulfate oxygen-18 values may not have been affected (Garchar and Arehart, 2008). Therefore, this remaining $\Delta^{18}O_{(SO4\text{-}H2O)}$ geothermometer appears to give more reasonable values than the rest of the geothermometers.

In the Antsirabe geothermal field, the temperature estimated to be 150°C is fairly in good agreement with the value of CO_2 partial pressure (9-13atm) at deep levels (Sarazin et al, 1986).

3.3 Energy Implications

Based on $\Delta^{18}O_{(SO4\text{-}H2O)}$ geothermometer temperatures, which should provide a conservative estimate, the following sites have the highest potential for electrical power production : Amparaky site No.20 (152°C) and Andranomangotraka site No.19 (149°C).

Based on chalcedony geothermometer, Sahasarotra site No.16 (149°C), Ranomafana II site No.2 (142°C) and

Ranovisy site No.9 (142°C) have relatively low geothermal potential.

It is also of interest to note that cold springs (e.g. Amparaky site No.20) can provide anomalous geothermometer temperatures indicating a geothermal resource, and that sampling of cold springs can be used as an exploration tool in areas with no surface expression of geothermal systems.

4. CONCLUSIONS

Over 20 available chemical analyses were obtained from springs collected in previous studies with previously limited or poor data. Major element chemical analysis indicates that hot springs and thermal waters for each studied area are likely from a single source. Minor differences in chemistry are likely a result of interaction of the thermal waters locally with different lithologies.

At most of the sites, it seems that the waters are not fully equilibrated, and hence, quartz, amorphous silica and Na-K-Ca geothermometer used in this research are approximately unreliable; however the $\Delta^{18}O_{(SO4\text{-}H2O)}$ temperatures and chalcedony temperature values seem more reasonable. In summary, the geothermal waters in the two areas (Antsirabe and Itasy) have temperature in the range 75 to 152ºC.

This conclusion is not especially helpful in determining whether or not the studied areas contain exploitable resource. This preliminary evaluation of geothermometer temperatures indicates that these areas have relatively low to medium geothermal potential; however, possible mixing and re-quilibration at lower, near surface temperatures needs to be evaluated at some of the sites.

For the future works, further investigation based mainly on thermal gradient drilling, geophysical and geological explorations, remote sensing and geothermal GIS, is necessary to determine the geothermal resource potential of selected sites (resource assessment) and to help identify if they have commercial reservoirs (production wells, capacity, nature of the waters, depth and temperature of the reservoir).

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