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Hydrogeochemical characterization of thermomineral waters in the central highlands of Madagascar

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Introduction

Hot springs are spread over Madagascar (Besairie, 1959). The volcanism in the Central region of Madagascar is particularly renowned for the existence of hot springs, mineral water, and thermal pools, but very few of them are closely studied. This work aims at characterizing the hot springs in the study region and bringing some hydrogeochemical explanations of their abnormal mineralization. Through physico-chemical analysis, the hydro-chemical facies of water samples collected at hot springs were determined using the Piper and Schoeller diagrams (Chandrasekharam & Bundschuh, 2002; Sadashivaiah et al., 2008; Chihi et al., 2015; Mohamed Salah et al., 2015). Hydro-chemical analysis reveals the quality of water providing useful information for its geothermal exploitation.

Geological setting of study areas

The study area (Figure 1) is a volcanic region (Vakinankaratra) where four eruptions phases occurred from Pliocene to Oligocene epochs (Rufer et al., 2009). The local geology is essentially characterized by trachyte, rhyolite, and basalt flows with a gneissic-migmatitic bedrock underlying. This bedrock belongs to the Antananarivo domain according to the geological subdivision of the Precambrian basement of Madagascar (Tucker et al., 2014). This region constitutes an inter-continental basin with tectonic origin (Rufer et al., 2009). Unconsolidated volcanic products, fluvio-palustrine floodplain series (10 m-thick), clay, silt and gravel alternate with ~0.1 m-thick peat horizons (Rasoanimanana, 2012).

The hot springs (Figure 1) emerge naturally with temperatures ranging from 27.6 °C to 55°C (Hambinintsoa, 2015). They are related to the volcanism and/or the tectonics of the study area. The open NNW – SSE and N-S fractures would constitute the main paths for hot water upflow (Sarazin et al., 1986; Hambinintsoa, 2015).

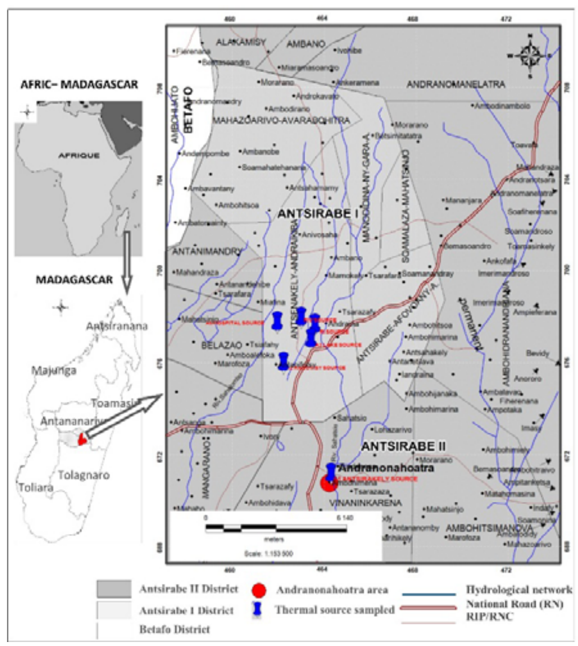

Figure 1: Location of the hot springs in the study area, with the two municipalities of Vinaninkarena (Antsirabe II) and Antsirabe I.

Methodology

In order to define the physical and chemical proprieties of the hot springs, several steps were undertaken from field sampling to laboratory analysis.

The water, which contained gas, was collected from the hot spring of the municipality of Vinaninkarena (Antsirabe II) A1 (Antsirakely thermal source) (Figure 1). For the other hot springs considered in this work (A2, A3, A4, A6, RI, RIV), the physical and chemical parameters were taken from previous studies, due to the unapproachable costs of the laboratory analysis.
The analysis of the Ranovisy hot spring (A2) was done by the SEER (Société d´Exploitation des Eaux de la Source de Ranovisy) Company in 2014 and by PRGM (Projet de Gouvernance de Ressources Minérales) in 1984.

The Lake hot spring (A3) was analyzed in 2004 by the CNRE (Centre National de Recherches sur l'Environnement) Madagascar laboratory. The Madagascar Mines services provided data from 2006 for the hospital hot spring (A6) and data from 1984 for the Ranomafana I (RI) and Ranomafana IV (RIV) hot springs.

In situ measurements

In the field, the location of the hot springs was registered with a GPS. pH, electric conductivity, water temperature were measured by using portable kit such pH-meter, conductimeter, electric probe, thermometer, and detector of exhausted gas.

Laboratory analysis

The chemical proprieties of Antsirake thermal water source (A1) were analyzed at the CNRE (*Centre National de Recherches sur l'Environnement)* Madagascar laboratory. The content of the main elements such calcium Ca^{2+}, magnesium Mg^{2+}, sodium Na+, and potassium K^{+} for cations, and sulfate SO_4^{-}, Chloride Cl^{-}, nitrate NO_3^{-}, carbonate CO_3^{2-}, and hydrogen carbonate HCO_3^{-} for anions, were measured. Total Dissolved Solid (TDS) content, hardness, alkalinity, and salinity were also determined. For the validation of our interpretations some physicochemichals parameters results of Antsirabe I thermal sources notably:the Ranovisy thermal source (A2), the Lake thermal source (A3), the hospital thermal source (A6), the Ranomafana I thermal source (RI) and the Ranomafana IV source (Figure 1) are considered in this work..

Data treatment

Schoeller Berkaloff and Piper diagrams are a graphical representation of the chemistry of a water sample.

Cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (SO_4^{2-}, Cl^{-}, NO_3^{-} and HCO_3^{-},) are shown in separate ternary plots in the Piper diagram, where different water samples can be grouped in hydro-chemical facies according to the dominant cation(s) or anion(s) (Sadashivaiah et al., 2008).

Schoeller Berkaloff diagram is represented by two axes: on the abscissa axis, the ions are listed, while on the ordinate axis ion content is plotted. The obtained points are connected by straight lines. The trend of the graph distinguishes the hydrochemical facies of the water. The maximum peaks (anion and cation) indicate the names of the facies.

Results

Physical and chemical general proprieties

The physical and chemical proprieties of the hot springs waters in our area for 6 samples (n=6) are resumed in table 1.

Table 1: Physical and chemical proprieties of water samples

Proprieties	Unity	Value (min –max)	Quality
pH		6,4 - 7,1	Neutral
SO_4^{2-}	mg/L	77-197	
HCO_3^{-}	mg/L	2400-3733	
Cl^{-}	mg/L	340-489	
CO_2	%	98,94-99,30	
Mineralisation	mg/L	>1500	Over mineralized
Total Hardness ($CaCO_3$)	mg/L	569<Ht<709	Hard
Alkalinity ($CaCO_3$)	mg/L	3000 - 3700	High
Total Dissolved Solid (TDS)	mg/L	2019-3058	
Electrical conductivity at T 20°C	µS/cm	3518 - 4870	
Hot spring temperature (Thermality)	°C	27.6	hypothermal
		35- 50	Thermal
		>50°C	Hyperthermal

The waters from thermal sources which distributed in two areas can be classified into three categories:

- Hypothermal source: A1 (Antsirakely) in the Antsirabe II;

-Thermal source: A2, (Ranovisy), A3, (Lake thermal source) and A6 (Hospital);

-Hyperthermal source: RI (Ranomafana I) and RIV (Ranomafana IV).

Compared to HCO_3^{-} content, SO_4^{2-} content is insignificant with average 165,88 mg/L. Thermal source (A1) has the minimum content 77 mg/L in the Antsirabe II, while the thermal sources (A2, A3, A4, A6, RI, RIV) in Antsirabe I area show similar value with 183,66 mg/L in average.

Concerning total dissolved solid content, Antsirakely source (A1) contains the minimal value (2019mg/L) in the Vinaninkarena area, while in Antsirabe I hot springs, the content varies from 2724.9mg/L (RI) to 3058.2 mg/L (A2).

For the chloride, its content varies from 240mg/L (RIV) to 489mg/L (A6) in the sources in Antsirabe I and it is about 340mg/L for Antsirakely hot spring.

Thermal sources have an important gas content, mainly 98% of CO_2 of all total gas in average (Moureu, 1926), which induced an estimated pressure about 9 to 13 atm (Sarazin et al., 1986). The average emanation flow measured of this gas is 35L/min and A2 present the highest value (50L/min). The CO_2 effect increase the hydrostatic pressure and promote water mineralization (over mineralized) by hydrolysis process, due to its role as aggressive acid to the aquifer rocks (Humez, 2012; Lions, 2013)

Hydro-chemical facies

The Piper and Schoeller diagrams (Figure 2 and Figure 3) indicate the predominance of the bicarbonate facies. The water tends also to the sodium pole.

Sodium bicarbonate waters facies include these following thermal sources: A1 (Antsirakely), A2 (Ranovisy), A3 (Lake thermal source), A6 (Hospital), RI (Ranomafana I), RIV (RanomafanaIV). These waters show a dominance of alkaline ions Na^{+} and K^{+}, chloride and sulphate ions. It is noted that the

Na^+ ion dominates largely the Ca^{2+} ion and Mg^{2+} remains always lower than K +.

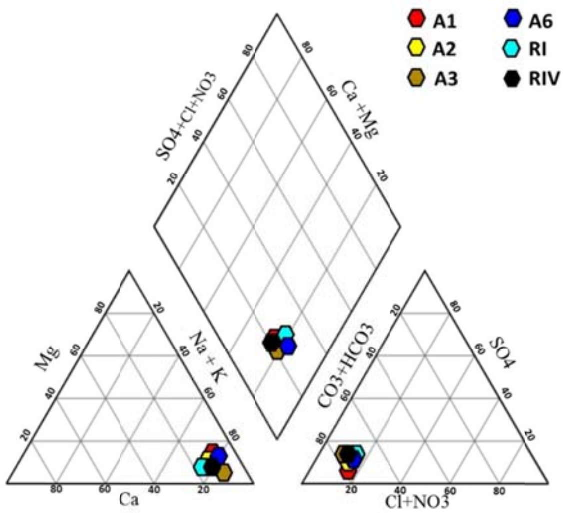

Figure 2: Representation of the thermal waters (A1, A2, A3, A6, RI, RIV) in Piper diagram *(Hambinintsoa, 2015)*

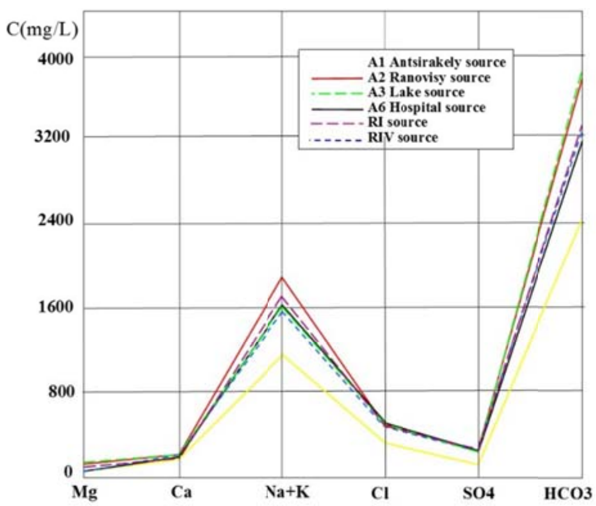

Figure 3: Representation of the thermal waters (A1, A2, A3, A6 and RIV) in Schoeller Berkaloff diagram

Conclusion

The characterization of the thermomineral hot springs based on hydro-chemical methods allowed to give an overview of the quality of the water in the aquifers in the Central region of Madagascar. Water quality was defined according the physical and chemical proprieties of 6 samples (n=6). Piper and Schoeller Berkaloff diagrams classified the water in bicarbonated-sodium facies. The importance of CO_2 pressure, and geological formations in the area and the potential impacts of CO_2 on groundwater resources, would explain that carbonic anhydride CO_2 is the main factor of the abnormal mineralization in major ion. The high content of bicarbonate, chloride ion and sulfate ion, is closely associated with the Ankaratra's volcanic activity.

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