Mozambique and the Feasible Development of the Geothermics – a First Geochemical Survey

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ABSTRACT

Mozambique has an extremely low sustainable access to energy partly due to the high cost of extending networks and increasing the number of connections in remote and relatively low demand area using conventional technologies. In this framework, the development of the geothermal energy both in direct and indirect uses can represent an important goal even if, presently, it is totally unused. At present there are not ongoing geothermal exploration and exploitation projects in Mozambique for low and medium-high temperature but the government and international experts are only just beginning to study geothermal resources in Mozambique. The present work proposes, for northern Mozambique, a review on available data about thermal waters, including new collected data.

A first geochemical survey was carried out in Northern Mozambique in March-April 2013, with the aim to investigate chemistry and origin of some thermal springs in the Tete Province. The investigated area is located in the East African Rift, adjacent to the marginal sedimentary Mozambique Basin. This area is crossed by the Rio Zambezi, one of the main river in Africa and explored during the 19th century by David Livingstone. A comparison with data from previous works was done.

Many thermal springs are present in this province due to the proximity with the rift, but considerably little geochemical and geothermal studies have been done, due to the difficulties related both to the site accessibility and social interaction with local tribes. The examined thermal waters have temperatures between 42°C to 80°C and are classified as chloride-sulphate alkaline waters (Cl-SO$_4$(Na, K)). Stable isotope δ^{18}D and δD and the slight O positive shift, suggest the presence of evaporation processes for deep fluids in a high temperature system. The estimated temperature of the potential reservoir ranges between 180 and 220 °C, for the area of Tete and Morrumbala. The potential reservoir seem to be promising, in particular for the area close to Tete City and Morrumbala. Probably, the resource is in fractured rocks associated to anomalous heat flux, with a maximum value of about 110 mW/m^2.

1. INTRODUCTION

Mozambique is located on the southeastern coast of Africa and borders with Zambia, Malawi, Tanzania, Zimbabwe, Swaziland and South Africa. The total area is about 800,000 km^2 and is divided into 11 provinces: Cabo Delago, Niassa, Niampula, Tete, Zambezia, Manica, Sofala, Inhambane, Gaza, Maputo Province and Maputo City. Mozambique suffers of the improper utilization of natural resources and access to energy in a sustainable manner remains extremely low. This situation is partly due to the high cost of extending networks and increasing the number of connections in remote areas using conventional technologies. The energy access is a prediction for economic development and social progress especially in the peri-urban and rural areas. Measures such as support programs for renewable energy related to energy efficiency need to be implemented in ways that will promote social and economic growth and sustainable development. In this framework the development of the geothermal energy both in direct and indirect uses can represent an important goal even if presently, it is totally unused. This paper presents a first review of available geochemical data relative to thermal waters located in Zambezia and Nampula Province, including three new springs sampled close to Tete City. Currently, this area is totally unexplored from the geochemical point of view. The study is specifically aimed at defining the origin of the emerging fluids and the potential temperature of the geothermal reservoir, based on major, minor and trace elements, isotopic signatures (δ^{18}O, δD) and geothermometric evaluations.

2. STATUS OF RENEWABLE ENERGY RESOURCES AND FOCUS ON GEOTHERMAL ENERGY

Mozambique's potential for power generation has been estimated at 14,000 MW (85% of which is hydropower). More than 80% of the hydropower potential is located in the Zambezi Valley, including the existing Cahora Bassa Dam (Hankins, 2009). The above evaluations do not include solar, wind, biomass and geothermal. At 2005, the Cahora Bassa Dam had an installed capacity of 2,075 MW (Mahumane et al., 2012) and it is the primary electricity source for the country, as well as a key source for Southern Africa. However, due to lack of power transmission lines and distribution networks, the availability of hydroelectricity for the time being is largely restricted to urban areas. In other areas electricity is simply not available, and where it is available, it is supplied by diesel generators. Other renewable resources have been confined, for about 90% (Chambal, 2010) , to traditional uses (i.e. wood for cooking) and rarely to off-grid power supply sources (photovoltaic, wind) (figure 1).
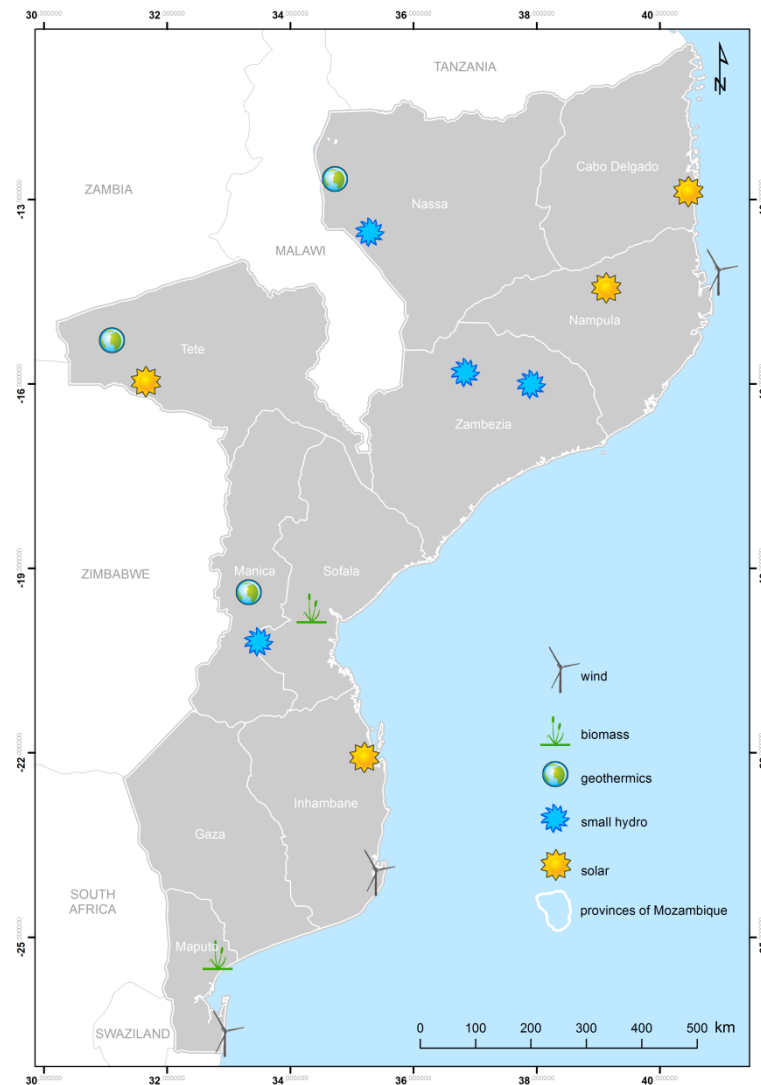
Figure 1: Distribution of the current recognized renewable resources. Other interesting areas could be exist, especially for unexplored geothermal fields (modified from Hankins, 2009).

2.1 Geothermal Energy

At present there are not ongoing geothermal exploration and exploitation projects in Mozambique both for low and medium-high temperature. Government and international experts are only just beginning to study geothermal resources in Mozambique. A preliminary evaluation of local geothermal potential in unexplored areas was completed by McNitt (1978, 1982) and it was evaluated at 25 MWe. The most promising areas are the northern and central provinces of Mozambique, especially within the East Africa Rift just north of Metangula, where heat-flow values range between 70 and 170 mW/m^2. Others interesting areas are long and to the west of major faults in the Espungabera-Manica areas, near the border with Zimbabwe (Martinelli et al., 1995).

2. STUDY AREA

2.1 Geological and Geochemical Setting

The investigated areas are located in Northern Mozambique, close to the marginal part of the western branch of the East African Rift (EAR), between the Zambezi and Lurio-Namama Belt. Mozambique has undergone several tectonic cycles, of which the most recent is the Post-Gondwana Cycle. The Post-Gondwana Cycle began in the country 175 Ma ago and consists of final break-up of the Gondwana continent followed by a phase of epeirogenesis, and several neo-rifting phases. The recent volcanism and anomalous topographic swells are associated with the rifting phases of the EAR. There are lowland <400 meters above sea level (m asl), made of Karoo to recent sedimentary formations, by highland plateaus and mountains of Archaic to Proterozoic crystalline formations (Steinbruch and Merkel, 2008). In terms of surface geology, the country is characterized by: crystalline and metamorphic terrains, mostly of Precambrian age forming the northern and western half Mozambique; late mesozoic and cenozoic sedimentary cover, forming a wedge thickening to the east and south that was in part deposited on the crystalline basement (Martinelli et al., 1995 and reference therein).

Tete Province: The geology of the Tete province is dominated structurally by the Zambezi Rift, which trends more or less W–E from the Zambia/Zimbabwe border along Cahora Bassa and then swings SE towards Tete and onwards to the coast of Mozambique. The rift formed in Proterozoic basement rock, developing into a zone of active extensional tectonism with sedimentary deposition. The Proterozoic basement comprises crystalline rocks such as gneiss, schists and meta-sediments.

The crystalline basement underlies the Tete Suite, that is overlapping by the Karoo sequences and Cenozoic marine sediments (Westerhof et al., 2008). The Tete Suite is composed predominantly of gabbro, leucogabbro and norite, with subordinate anorthosite and minor but widespread ultramafic rock types, mostly pyroxenite, and rocks mainly composed of iron-titanium oxides. Rock fabrics are generally massive and medium- to very coarse-grained or even pegmatitic. The host rocks of the Tete Suite were subjected to a later igneous phase(s) which resulted in the intrusion of numerous northeast-southwest oriented dolerite dykes. Karoo rocks (Carboniferous–Jurassic) were deposited within sedimentary basins on the tectonically active basement floor. The Karoo Supergroup cover the Suite unconformably whereas the contact of that with the crystalline basement is tectonic.

Zambezia-Nampula Province: The other study area is located in Zambézia province, geologically it is situated within the Nampula Complex which is the largest and southernmost of several Proterozoic crustal blocks making up the crust of northern Mozambique (Thomas et al., 2010; 2011). The Nampula Complex is the structurally lowest of these Mesoproterozic tectono-stratigraphic crustal blocks. The lithodemic and lithostratigraphic units comprise a sequence of supracrustal gneisses and metavolcanic rock assemblage, the Molócuè Group (ca. 1090 Ma), which is migmatised to various degrees, and an even older suite of granitoid gneisses known as the Mocuba Suite (ca. 1125 Ma). These supracrustal and granitoid rocks were intruded by various intermediate to acid intrusives, now granitic orthogneisses, termed the Culicui Suite (ca. 1070 Ma; Direcção Nacional de Geologia, 2007; Macey et al., 2010; 2011). All rocks underwent pervasive tectonic reworking during the late Neoproterozoic-Cambrian, the Pan-African collision orogeny at ca. 550 Ma, which led to the assembly of the constituent crustal blocks (Thomas et al., 2010; 2011). The current distribution of rock types and virtually all the fabrics seen in the rocks of the Nampula complex are considered to be due to the Neoproterozoic orogeny which destroyed almost all the evidence of earlier fabrics and structures (Macey et al., 2010).

Previous works (Martinelli et al., 1995 and reference therein; Steinbruch and Merkel, 2008) recognized at least 39 thermal springs located in the Manica area, close to the border with Zimbawe and in the north close to the border with Zambia and Malawi. Here there are the most interesting sites, within the rift just north of Metangula on Lake Niassa. Thermal springs in Mozambique occur along rift borders, in conjunction with main fractures of mobile belts, reactivated tectonic blocks, and ancient volcanic zones. The temperature ranges from 37°C to 95°C, usually the water with temperature major than 50°C are associated with rift margins (Lachekt, 2004).

3. METHODS

A total of 11 thermal water samples were investigated to characterize the potential geothermal reservoir of Northern Mozambique. This includes new data (3 samples) from one sampling campaign in 2013 and a comparison with data from Martinelli (1995). The locations of the examined thermal waters are shown in figure 2. Sample names, province, site, features as well as on-site characteristics, chemical composition and references are listed in table 1.

The new sampled thermal springs were collected from March and April 2013 within of the Tete Province (Northern Mozambique). Temperature, pH, Eh, electrical conductivity values, and alkalinity (titration with 0.05 N HCl), silica (spectrophotometry) were determined in situ. Water samples were filtered (0.45 μm) and stored in high-density polyethylene flacons for laboratory analysis. Major anions (F^-, Cl^-, Br^-, SO_4^{2-} and NO_3^-) and cations (Ca, Mg, Na and K) were analyzed by ion-chromatography (Dionex, DX500) on filtered and filtered and acidified samples, respectively. Minor and trace elements (B, Li and Sr) were determined on filtered and acidified samples by ICP-MS. An unfiltered diluted sample (1:10) was collected for the determination of SiO_2 by molecular spectrophotometry. The analytical error for major and minor and trace compounds error was 5 and 10%, respectively.

The $^{18}O/^{16}O$ and $^2H/^1H$ isotopic ratios (expressed as $\delta^{18}O$ and δD ‰ vs. VSMOW) were determined using an Analytical Precision AP 2003 spectrometer and a Finnigan MAT Delta plus spectrometer, respectively. The analytical precision is 0.1‰ for $\delta^{18}O$ and 1‰ for δD.
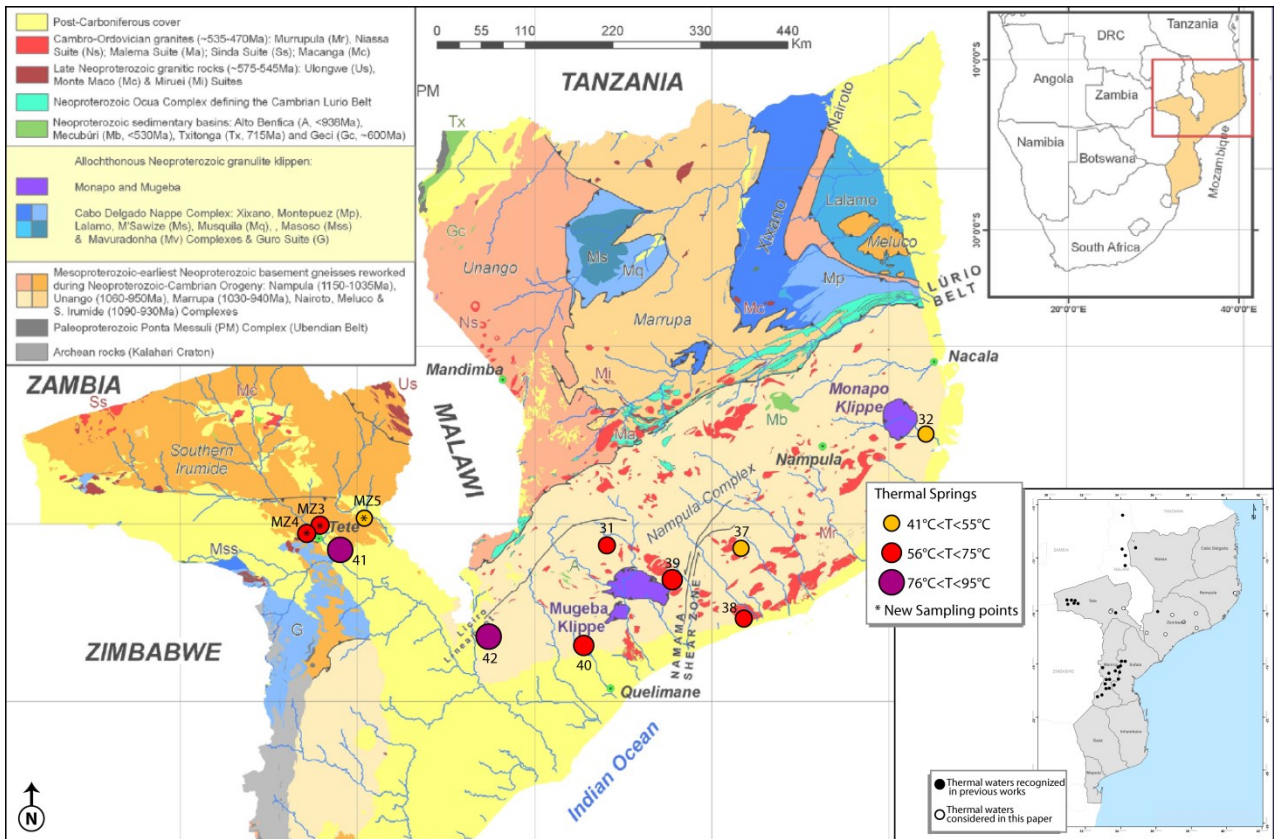
Figure 2: Geological map of Northern Mozambique and locations of the examined thermal springs (modified from Macey et al., 2010). All the thermal waters recognized in Mozambique, from previous work, are shown (black dots) on the bottom right side of the figure. The examined waters are indicated with white dots.

4. RESULTS AND DISCUSSION

4.1 Geochemical Characteristics

The examined thermal waters have temperatures from 42 to 80 °C, high total dissolved solids (TDS) up to 8000 mg/L and show a chloride-sulphate alkaline (Cl-SO$_4$(Na, K)) composition (Figure3). These waters have sodium as the major cation and chloride as the major anion. The silica concentration does not exceed the 100 mg/L. The δ^{18}O and δD values, available only for the new data (MZ3, MZ4, MZ5), range from -6.75 to -6.78‰ and from -44.73 to -44.89‰ vs. SMOW, respectively.
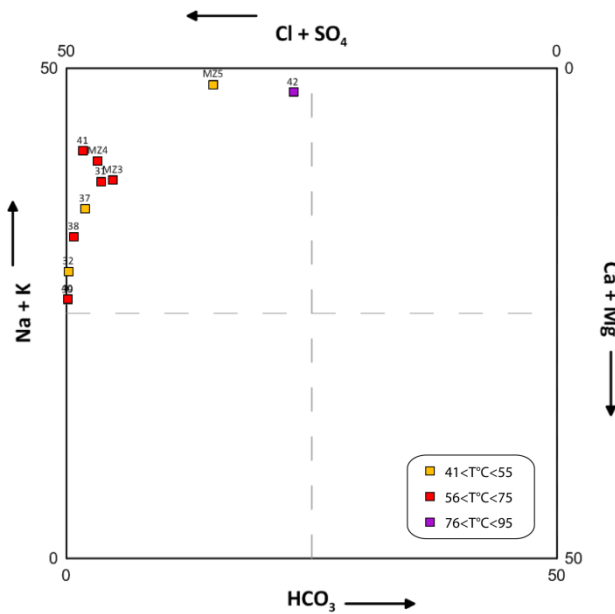

Figure 3: Langelier and Ludwig diagram for the investigated samples.

Sample	Province	Site	Type	Date	Physical parameters				Isotopic composition		Chemical composition								Reference
					T (°C)	Altitude (m)	Eh (mV)	TDS (mg/l)	$\delta^{18}O$ (‰)	δD (‰)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^+ (mg/l)	K^+ (ppm)	Cl^- (mg/l)	SO_4^{2-} (mg/l)	HCO_3^- (mg/l)	SiO_2 (mg/l)	
MZ3	Tete	Nhawóndòc	ts	04.2013	66	158	-209	1426	-6.79	-44.78	98.1	<0.01	363.3	29.0	435.3	372.1	128.1	46.1	new data
MZ4	Tete	Tenta	ts	04.2013	52	121	-323	1368	-6.75	-44.89	77.1	<0.01	368.0	9.68	442.0	376.0	85.4	52.7	new data
MZ5	Tete	Mauira	ts	04.2013	42	339	-404	861	-6.53	-42.73	8.18	<0.01	268.0	21.3	266.0	66.1	231.8	34.3	new data
31	Zambezia	Munhamade	ts	1959	63		-	948	-	-	52.0	0.96	204.5	0.39	67.4	467.3	53.7	87.0	Martinelli et al., 1995
32	Nampula	Mossuril	ts	1959	46		-	7982	-	-	1108.0	5.76	1810.1	8.58	4282.6	644.6	36.6	29.0	Martinelli et al., 1995
37	Zambezia	Gilé	ts	1959	52		-	602	-	-	94.8	2.40	273.7	14.8	152.4	590.8	40.3	81.2	Martinelli et al., 1995
38	Zambezia	Mualama	ts	1959	64		-	1777	-	-	176.0	2.40	376.51	31.6	428.9	635.2	24.4	63.6	Martinelli et al., 1995
39	Zambezia	Maganja	ts	1959	73		-	5489	-	-	856.8	0.84	1051.1	81.5	2857.4	483.2	17.7	81.0	Martinelli et al., 1995
40	Zambezia	Namacurra	ts	1959	75		-	8147	-	-	1264.0	3.96	1603.1	67.5	4853.9	268.5	17.7	87.2	Martinelli et al., 1995
41	Tete	Niaondive	ts	1959	80		-	1554	-	-	73.6	0.96	414.5	19.1	436.1	444.3	45.8	95.6	Martinelli et al., 1995
42	Zambezia	Morrumbala	ts	1959	78		-	626	-	-	6.00	1.08	168.1	8.19	95.7	75.9	224.5	97.2	Martinelli et al., 1995
MW	Tete	Luenha	mw	04.2013	-	-	-	-	0.21	12.25	-	-	-	-	-	-	-	-	new data

Table 1: Physical, chemical (major elements) and isotopic data of thermal waters in Northern Mozambique (Tete, Zambezia and Nampula Province). The isotopic composition is expressed in ‰ versus V-SMOW. "ts" means "thermal spring", "mw" – "meteoric water", "-" – "not determined".

Geothermometers	Equation	Reference	Sample (estimated T °C)										
			MZ3	MZ4	MZ5	31	32	37	38	39	40	41	42
Quartz 1	$t = \dfrac{1309}{5.19 - \log(SiO2)} - 273.15$	Fournier (1977) (no steam loss)	138	145	123	177	113	172	157	172	177	183	184
Quartz 2	$t = \dfrac{1522}{5.75 - \log(SiO2)} - 273.15$	Fournier (1977) (max. steam loss)	133	140	120	165	112	162	149	162	166	171	172
α Cristobalite	$t = \dfrac{1000}{4.78 - \log(SiO2)} - 273.15$	Fournier (1977)	87	95	72	127	63	122	106	122	127	134	135
Chalcedony	$t = \dfrac{1032}{4.69 - \log(SiO2)} - 273.15$	Fournier (1977)	111	120	94	155	84	150	132	150	155	162	164
Na-K-Mg	$t = \dfrac{1390}{1.75 - \log(Na/K)} - 273.15$	Giggenbach (1988)	215	144	215	38	68	188	219	213	172	177	181
	$t = \dfrac{4410}{14.0 + \log(K2/Mg)} - 273.15$		-	-	-	25	69	93	114	163	130	113	88

Table 2: Estimated temperatures for different geothermometers.

The δD vs. $\delta^{18}O$ diagram the thermal waters of Tete Province plot close to the Provinceal Meteoric Water Line (RMWL: $\delta D = 7.4 \, \delta^{18}O + 9.0$; Rozanski et al., 1996) but on the right side, showing a positive shift of the $\delta^{18}O$ (Figure 4). This slight positive shift can be interpreted as due to evaporation of deep fluids in a high temperature system.
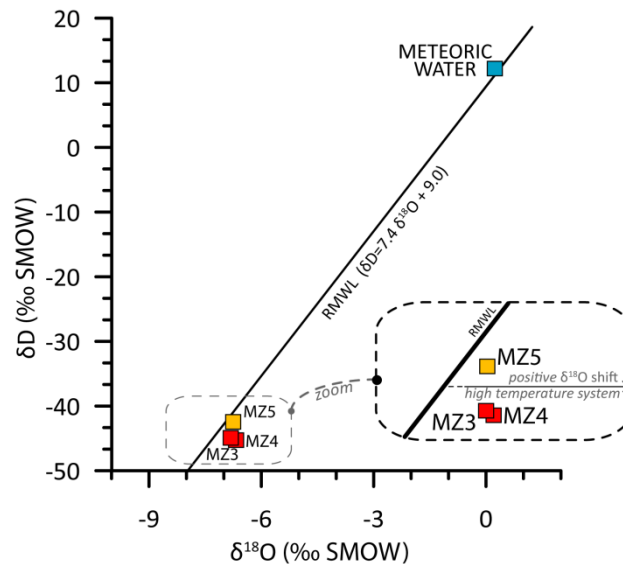

Figure 4: δD vs. $\delta^{18}O$ diagram for the analysed thermal waters (new data-Tete Province).

4.2 Geothermometric Evaluations

The application of geothermometric techniques in liquid phases is always a difficult task, especially when performed on a country-wide scale. Re-equilibration of rising deep hydrothermal hot fluids to shallower conditions and/or mixing with cooler shallower fluids may affect the interpretation of the data. Liquid phase geothermometers are commonly divided into i) those that re-equilibrate relatively fast at decreasing temperature during fluid upflow towards the surface, such as the silica geothermometers, and ii) those that retain the deep fluid characteristics also at lower temperatures, such as the Na/K geothermometers in its various formulae. The technique proposed by Giggenbach (1986, 1988), that combines in a single ternary diagram Na-K-Mg, was applied to the examined samples.

This ternary diagram (figure 5) is based on the premise that fluids circulating in hydrothermal system interact with primary minerals that are altered to secondary minerals. The relative concentrations of Mg^{2+}, Na^+ and K^+ in the hydrothermally-derived solutions from water-rock interaction, are fixed by thermodynamic parameters, mainly the temperature, of alteration reactions occurring within the hydrothermal system.

The figure 5 shows that most examined thermal waters fall in the field of the *partial equilibrium,* referred to intermediate conditions between simple rock dissolution at low temperatures and hydrothermal conditions at higher temperatures. Only the sample 37 (Gilé) lies in the area of the *immature waters* indicating a partial solubilization of Mg^{2+} from alterable minerals.

The samples 37, 42, MZ3 and MZ4 are clearly positioned in the full equilibrium, in particular the thermal waters of Nhawóndòc, Tenta and Morrumbala (MZ3, MZ4 and 42) are close to a temperature range between 180 and 220°C, showing a possible upflow of hydrothermal solutions. To this end, it is possible to invoke the isotopic composition of ^{18}O in the δ^{D}- $\delta^{18}O$ diagram that suggests, for the samples MZ3 and MZ4, a slight "high temperature" shift for O. On the contrary, for the sample MZ5, falling in the partial equilibrium, the isotopic composition of ^{18}O suggests a minor contribution or absence of hydrothermal solutions and a prevalence of shallow components.

The silica geothermometer is based on the solubility of quartz. The silica content of water from a hot spring or well can be correlated with the last equilibrium temperature with quartz. The quartz geothermometer works best for temperature between 150 and 225°C (Fournier, 1977). At higher temperatures silica is likely to deposit during ascent of the water. Temperatures obtained from silica content (table 2) are lower than those from the alkali geothermometers and provide calculated temperatures <180°C, this can suggest slow upflow of the water and a major sensitivity to boiling processes with a consequent riequilibrium of the fluid.
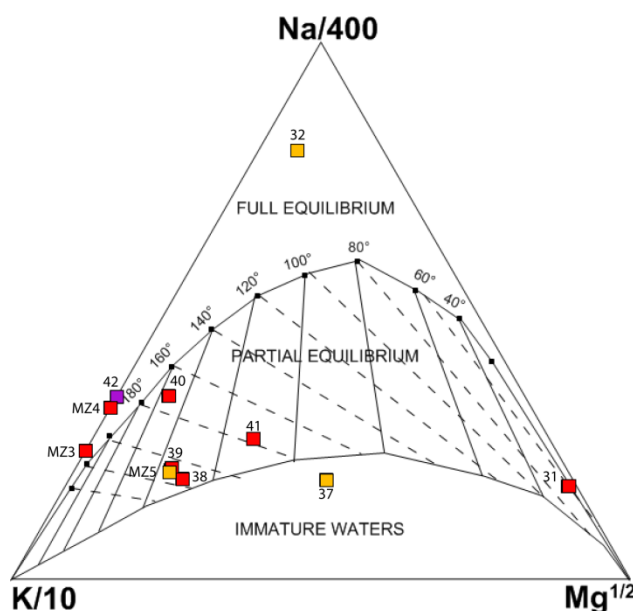
Figure 5: Ternary K/10–Na/400–Mg0.5 diagram for the investigated thermal waters.

5. CONCLUSIONS

The geochemical characteristics of the thermal springs in Tete Province and Zambezia Province are classified as chloride-sulphate alkaline (Cl-SO$_4$(Na, K)).

Stable isotope δ^{18}D and δD and the slight O positive shift, suggest the presence of evaporation processes for deep fluids in a high temperature system.

The estimated temperature of the potential reservoir ranges between 180 and 220 °C, for the area of Tete and Morrumbala.

According to the characteristics of the thermal waters, the geothermal resource in the investigated areas seems to be promising, in particular for the area close to Tete City and Morrumbala. These areas were never been considered in the past as potential geothermal resources. Probably, the resource is in fractured rocks associated to anomalous heat flux, with a maximum value of about 110 mW/m^2. However, data and information on the geological and structural setting of the potential geothermal systems are scarce, so it is not possible to develop a geothermal reservoir model and to evaluate the potential power capacity of the fields. Further studies to clarify the structure of the resources have been necessary.

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