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The Geothermal Potential of Ambilobe and Sambirano, North Madagascar

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ABSTRACT

Madagascar intends to reduce its dependence on fossil energy and to mitigate carbon emissions through its energy transition policy by developing alternative and renewable energy from solar, wind, hydro and geothermal energy. This work aims to present an overview of the geothermal potential of one of geothermal regions identified in Madagascar. The North region was investigated for geothermal resource potential, where hot springs with temperature up to 48°C are found at surface. Ambilobe and Ambanja, the two prospects geothermal areas in the North region, consist of normal fault zones with sedimentary-basement contact and graben structures. Quaternary volcanic rocks, mainly basalt, Permian and Triassic sediments dominated by shale and sandstone, which overlie a faulted and fractured Proterozoic metamorphic basement dominantly composed by micashist, gneiss and amphibolite, constitute the main geological units of those areas.

A conceptual model of geothermal systems of each prospect area was built, as a first assessment of the geothermal potential in this region, to describe and illustrate essential geological features. Then, hydraulic and thermal properties of rock samples collected from outcrops were measured in laboratory to identify heat transfer processes prevailing in the geothermal systems. The highest values of porosity of 8.7% and 10.7% are found in Permian-Triassic sandstones and in the micashist, respectively. The matrix permeability of sedimentary formations varied around 8.0 mD (7.9×10^{-15} m^2) with an average thermal conductivity around 3.6 W m^{-1} K^{-1}, while the basement rocks have a permeability ranging between 0.001 mD md (**9.9×10^{-19}m^2**) and 10.1 mD (**1.0×10^{-14} m^2**) and an average thermal conductivity around 2.7 W m^{-1} K^{-1}. The characteristics of geothermal systems in North of Madagascar share similarities with other geothermal systems in the world that have successfully harnessed resources with low-to moderate enthalpy. Ambilobe shares similarities with geothermal systems in western Great Basin in the Basin Range in America, whereas Ambanja is more comparable to geothermal systems in western Turkey.

1. INTRODUCTION

At the early exploration stage, characterization of geological formations based on surface observations can give a general understanding and overview of the geothermal resource types, in order to define their use and anticipate heat transfer mechanisms prevailing at depth. In fact, basic geological information and temperature data from surface manifestations such as hot springs are key parameters to define conceptual models, which is the baseline information needed to characterize the geothermal systems (Cumming, 2009; Axelsson, 2013). Additionally, a definition of thermal and hydraulic properties of the main lithological units outcropping at the study areas can help identify dominant heat transfer mechanisms at depth (Sass et al., 2012). The acquisition of such data is essential before proceeding to subsurface studies and to help justify drilling of boreholes that can better define resources and help envision possible scheme of exploitation.

Although identified in the 1980s by Gunnlaugsson et al. (1981), the geothermal energy potential of Madagascar still has to be defined in order to advance the stage of resource development. In this paper, the two areas Ambilobe and Ambanja in the North region of Madagascar are studied to better define the geothermal resources that could be exploited for direct use purposes and electricity generation. The geothermal systems in the both areas are commonly associated with extensional domains referred to as geothermal plays where geothermal systems in Ambilobe are classified as graben border-fault, liquid-dominated moderate temperature whilst geothermal systems in Ambanja area as a fossil magmatic liquid-dominated moderate-temperature system (Rajaobelison et al., 2020). A first conceptual model of geothermal systems of both fields of interest is proposed and proprieties such as permeability, porosity, thermal conductivity and diffusivity as well as specific heat capacity of the main lithological units are evaluated.

2. GEOLOGIC SETTINGS

2.1 Ambilobe

Ambilobe area is characterized by a normal fault zone named Andavakoera, delineating the sedimentary rock to basement contact (Figure 1a and 1b). It forms a 120 km long depression with 3 to 5 km average width. It is oriented NE-SW in the direction of major active faults which have affected the basement and its sedimentary cover since the Trias (Lardeaux et al., 1999). Undifferentiated faults and dextral or senestral strike-slip faults are also observed (Figure1b). The Proterozoic basement is dominantly characterized by micashist from Betsiaka group, granitic orthogneiss of Antsirabe North suite and garnet-amphibolite of Milanoa group, which are stabilized in greenschist and amphibolite facies of metamorphism (Thomas et al., 2009; Tucker et al., 2014). Meter-width quartz-barite-veins intersect the sediments as well as the micashist formation. They have the same strike, N050° to 150°, as the extension fractures and faults that affected sediments cover and basement formation. The sedimentary sequence found is part of Ambilobe basin. It is constituted of Permian sandstones and conglomerates of the Sakamena group which is covered by Eotriasic shales and the

upper Triassic sandstone of the Isalo I group. This latter unit overlies either the Permo-Triassic deposits or directly the Proterozoic basement. This Isalo I sandstone forms an imposing escarpment of 400 to 500 m high along the depression dipping between 5 to 30° to the northwest. Recent alluvial deposits are found in the depression on top of the Ambilobe basin sequence.

2.2 Ambanja

The Ambanja area is characterized by a 25 km long graben oriented in the NW-SE direction having an average width of 4 km (Figure 1c). The date of the brittle tectonic activity that generated the Sambirano graben is not exactly known, but most probably formed during the early Tertiary according to Rossi (1980) or late Cretaceous, before the first volcanic eruptions in this area. The Proterozoic basement rocks belong to the Sambirano-Sahanta group. These rocks are mostly quartzite and paragneiss, which were intersected by Cambrian undifferentiated syenite intrusion of the Ambalavao-Maevarano suite. The Triassic sandstone deposits of Isalo I group appears only in the north-west which overly the fractured Protérozoic basement. The Quaternary volcanic rocks are represented mainly by basalt while volcanic deposits such as ignimbrite, tuff and breccia with thicknesses between 600 and 700 m have been observed mostly in the southern part of the graben. These are pyroclastic deposits originating from the neighbouring stratified Neogene to Quaternary volcanic complexes of Tsaratanana (Rossi, 1980; Estrade, 2014). The graben depression was filled with recent detrital and alluvial sediments.

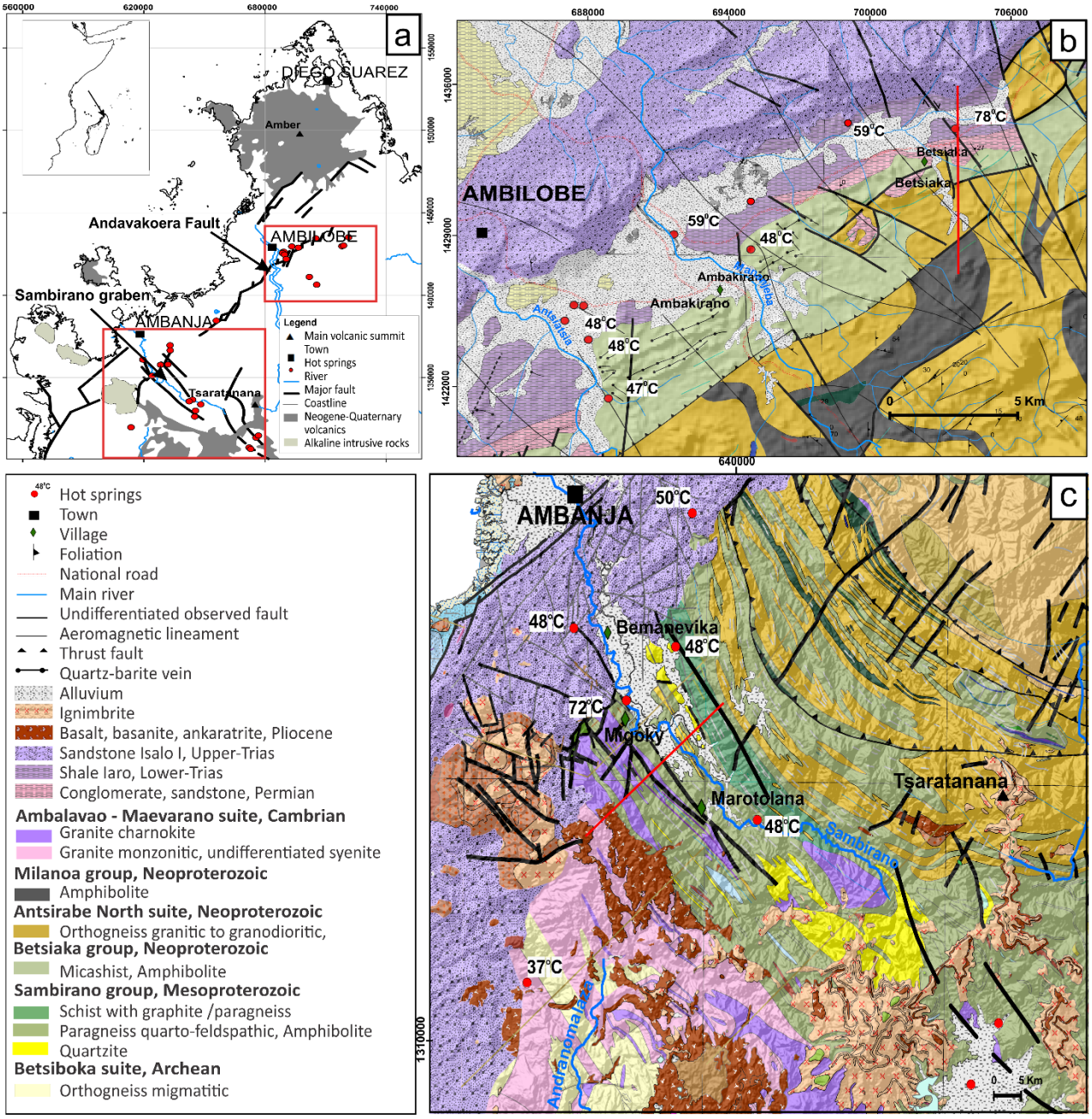


Figure 1: (a) Location of Ambilobe, Ambanja geothermal areas and (b), (c) detailed geology with position of thermal springs of Ambilobe and Ambanja geothermal prospects (modified from Roig 2012).

3. CONCEPTUAL MODEL

For each prospect area, a conceptual model was defined, trying to identify the sources of heat, the potential permeable geological formation and indicate the general pattern of the flow of fluids and the recharge zones. The models are presented with interpreted 2D cross sections, in which physical features of the system are drawn. They are descriptive or qualitative models, built to better understand factors controlling fluid migration. The model takes into account all data collected, including results of chemical and isotopic content of fluid in surface manifestations and chemical geothermometers (Gunnlaugsson et al., 1981; Sarazin et al., 1986; Hambinintsoa et al., 2017). The surface exploration such as geological and structural maps as well as remote sensing interpretations helped to review the tectonic framework of Madagascar (Collins, 2006; Roig et al., 2012; Tucker et al., 2014). Geophysical surveys, and seismic data which provide the information of average thickness of the Madagascar crust and uppermost mantle (Andriampenomanana et al., 2017; Pratt et al., 2017; Rindraharisaona et al., 2017), offered a general understanding of the lithospheric structure of Madagascar (Wysession et al., 2016; Paul et al., 2017).

4. LABORATORY ANALYSIS

Around 60 rock samples covering Quaternary volcanics, Permian and Triassic sediments and Proterozoic metamorphic basement, which are the main lithological units in the study area, were collected from 17 outcrop locations and analysed. For statistical purposes, 3 to 10 single measurements of the different rock properties were conducted on each rock sample. Sedimentary rocks and basement rocks were dried for 12 hours in a conventional oven at 115°C before the measurements. The steps to determine the thermohydraulic proprieties are summarized by the scheme of Figure 2.

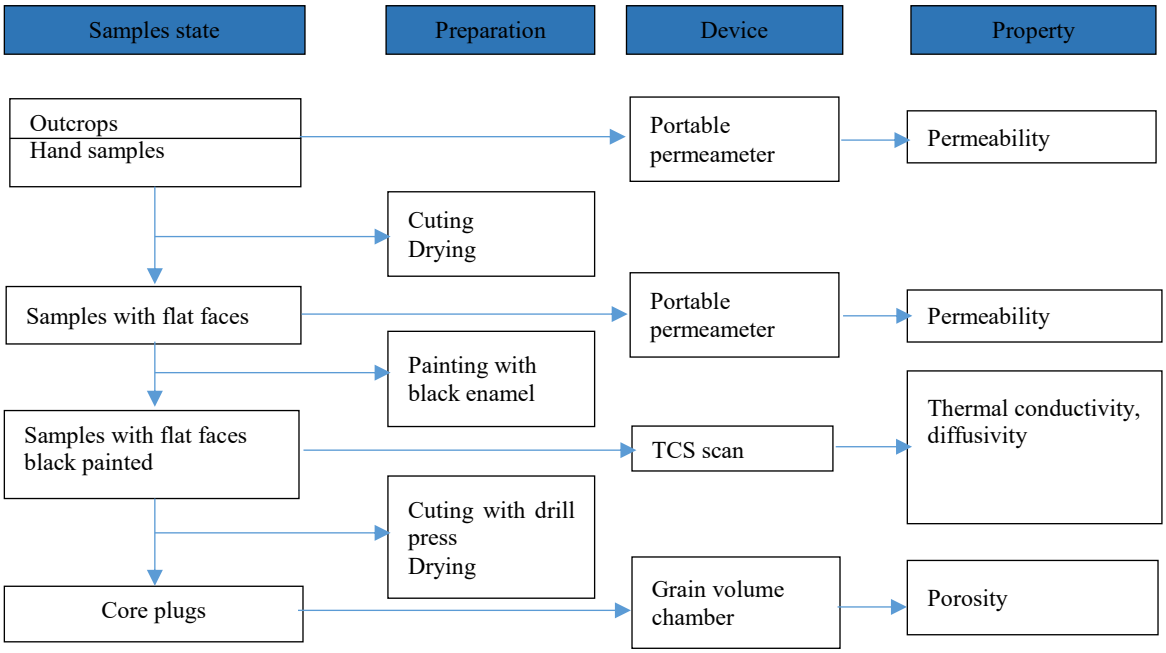


Figure 2: Steps followed for thermos hydraulic assessment of rock samples.

4.1 Hydraulic properties

4.1.1 Permeability in atmospheric pressure

The portable probe permeameter PPP 250TM from Core Laboratories (Core Lab, 2016) was used to measure air permeability directly on outcrops and on samples in laboratory, where the majority of measurements was made. The transient pressure decay method is used with this device, injecting compressed air with initial pressure set to 35 psi in the rock (Core Lab, 2016). The probe tip with a neoprene seal is pressed against a flat rock surface. When the gas diffuses into the rock, the rate of pressure decay is monitored and the decay is faster with a higher permeability. The permeability evaluated with this instrument is in a range of 0.001 mD to 5D. Measurements were made parallel or perpendicular to bedding, lamination or rock foliation planes. Klinkenberg corrections (Tanikawa et al., 2009; Al-Jabri et al., 2015) cannot be performed with this instrument since analyses are carried out at atmospheric pressure.

4.1.2 Porosity measurements

An AP-608 automated permeameter-porosimeter from Core Test Systems (Coretest Systems, 2017) coupled with a grain volume measuring chamber was used for the evaluation of porosity with core plug samples. Porosity calculations are based on grain volume measurement. Pore volume $\emptyset$ (%) was determined by subtracting the grain volume V_{gr} (m^3) from the bulk volume V_{bl} (m^3) and by dividing by the bulk volume:

$$\emptyset = \frac{V_{bl} - V_{gr}}{V_{bl}} \times 100 \quad (1)$$

where $\emptyset$ is the porosity, V_{bl} (m^3) the bulk volume and V_{gr} (m^3) is grain volume.

Grain volume measurements were performed using helium expansion based on Boyle's Law, where the pressure exerted by a given mass of an ideal gas is inversely proportional to the volume it occupies (American Petroleum Institute, 1998). A cylindrical core plug, with a diameter of 25.4 mm, and length of 25.4 to 101.6 mm was prepared from each sample collected in outcrops. The volume of grain in the rock is determined from the initial pressure of the gas chamber and the core chamber pressure at equilibrium, assuming a constant temperature and number of gas moles. Porosity evaluation is made at a 13.8 bar with a measurement range of 0.1 to 40% (Coretest Systems, 2017).

4.2 Thermal properties

The optical scanning method was used with an infrared scanner developed by LGM Lippmann to determine transient thermal conductivity and diffusivity (Popov et al., 1999; Popov et al., 2016). Flat surfaces of hand samples were painted with black enamel to ensure proper infrared absorption. Then, samples were placed between references materials and analysed along a scan line where a moving optical head with an infrared heat source and temperature sensors scan thermal properties. The standard references are two quartz and titanium alloy couples with known thermal conductivity and thermal diffusivity, respectively, 0.70-1.35 $Wm^{-1} K^{-1}$, 0.40- 0.83 $m^2 s^{-1}$, and 6.52-13.3 $Wm^{-1} K^{-1}$, 2.74-3.58 $m^2 s^{-1}$. They are strongly recommended for measuring properties of natural rock materials (Popov et al., 2016). The temperature sensors are located before and after the heat source to measure undisturbed, or cold, and disturbed, or hot, temperature from which the thermal conductivity λ ($Wm^{-1} K^{-1}$) and diffusivity α ($m^2 s^{-1}$) are calculated according to comparative measurements performed on reference samples placed before and after the rock sample. The local evaluation of thermal properties along the scan line allows identification of heterogeneity due to variability in mineralogical composition, porosity, fractures density, inter grain contacts and cementation, pore and fracture aspect ratio. Measurements were made parallel and perpendicular to bedding, lamination structures or rock foliation plane at a scanning speed of 5 mm s^{-1}. The volumetric heat capacity ρc (MJ K^{-1} m^{-3}) was deduced from thermal conductivity and diffusivity measurements:

$$\rho c = \frac{\lambda}{\alpha} \quad (2)$$

where c (J K^{-1} kg^{-1}) is specific heat capacity.

5. RESULTS

5.1 Conceptual model of Ambilobe area

A conceptual model of Ambilobe geothermal system in the Andavakoera fault zone is represented by an N-S 2D cross section (Figure3). Thermal springs emerge mainly along the NE-SW direction of the depression through fractures and faults affecting the shale unit at surface, which is the case of the majority of springs near to the Ambakirano village and the Betsiaka spring (Figure1b). Those springs can possibly originate from the Permian sandstone which is believed to be a possible reservoir rock. As shown in the conceptual model, the fluids can circulate from north to south following the general topography. The springs in the mentioned villages reach the surface at a temperature of 59°C and 78°C, respectively, and according to chemical geothermometers, the average reservoir temperature would be 140°C to 180°C in this zone (Gunnlaugsson et al., 1981). The hot spring water has moderate to high carbon dioxide concentration, which might cause a calcite scaling and corrosion problems during geothermal exploitation (Gunnlaugsson et al., 1981)

The heat source can be originated from the thermal gradient caused by the thinning of the crust in this region, with an average thickness of 33 km of which 5km of sediments, where the base of the lithosphere is encountered at 50 km depth (Andriampenomanana et al., 2017; Pratt et al., 2017).

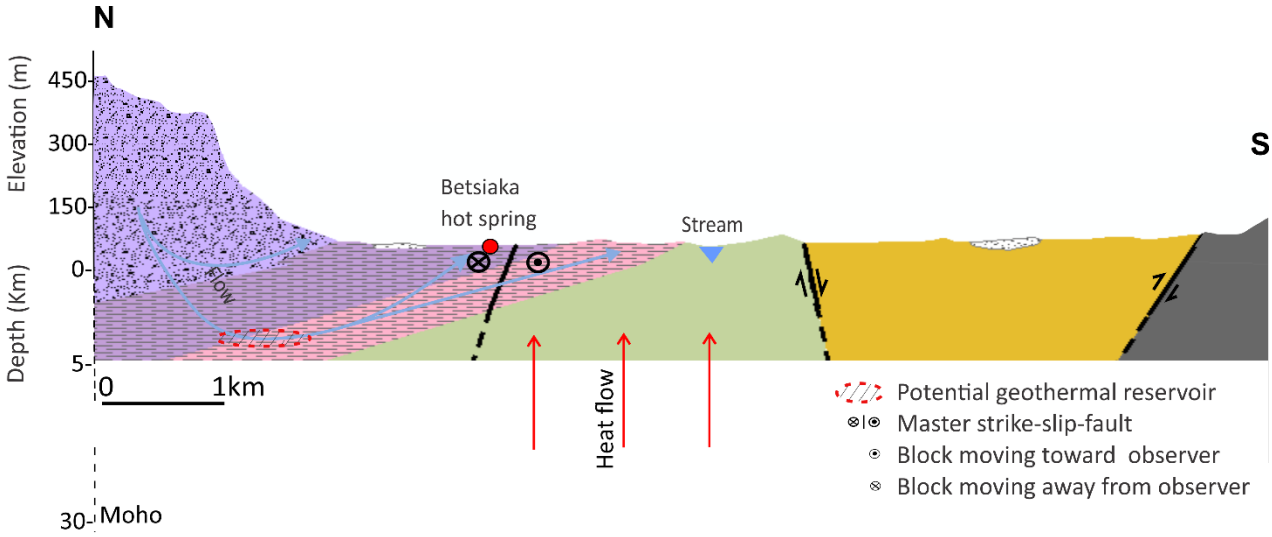


Figure 3: Conceptual geothermal model of Ambilobe area in Andavakoera normal fault zone (legends same as Figure 1b). Vertical scale of exaggerated elevation profile is different from the depth's scale based on the structure of crust and uppermost mantle beneath Madagascar (Andriampenomanana et al., 2017)

5.2 Conceptual model of Ambanja area

A conceptual model model of Ambanja geothermal system in Sambirano graben is represented by a SW-NE 2D cross section perpendicular to the graben structure (Figure 4). As shown on the map of Figure 1b, hot springs emerge mostly in the basement side, through NW-SE fractures bounding or parallel to the graben elongation, which is the case of majority of springs near to Bemanevika and Migoky villages. The conceptual model proposes that the fractured paragneiss would be considered as the most permeable unit for underground fluids flow. Then, NW-SE graben faults, whose depth has not been determined yet, can be a potential flow path to bring fluids near surface. The fluids circulate mainly in the SW-NE direction, consistent with the topography, where recharge occurs along topographic highs (Figure 4). The springs at the surface reaches the temperature of 48°C to 72°C in this area where Gunnlaugsson et al. (1981) estimated from chemical geothermometer, that the temperature of the fluid with low concentrations of solids and dissolved gases, can reach 140°C to 200°C inside the reservoir. This temperature range correspond to a moderate enthalpy fluid (Hochstein, 1990; Dickson et al., 2003; Sanyal, 2005)

The source of heat is likely to originate from a fossil magma chamber in the continental crust which is associated with the alkaline intrusive complexes in the north of Madagascar and beneath the volcanic massif of Tsaratanana as shown also in Figure 1a. The intrusive complexes formed during a first period of volcanism from 27 Ma to 20 Ma and followed by a more recent period, from 17 Ma until today for Tsaratanana massif, Nosybe and Amber area (Estrade et al., 2014; Cucciniello et al., 2016). The decay of radiogenic elements in recently crystallized rock may be providing additional heat to the heat originating from a shallow mantle in the Ambanja area. The average thickness of crust and lithosphere depth are the same as found in Ambilobe area (Andriampenomanana et al., 2017; Pratt et al., 2017; Rindraharisaona et al., 2017).

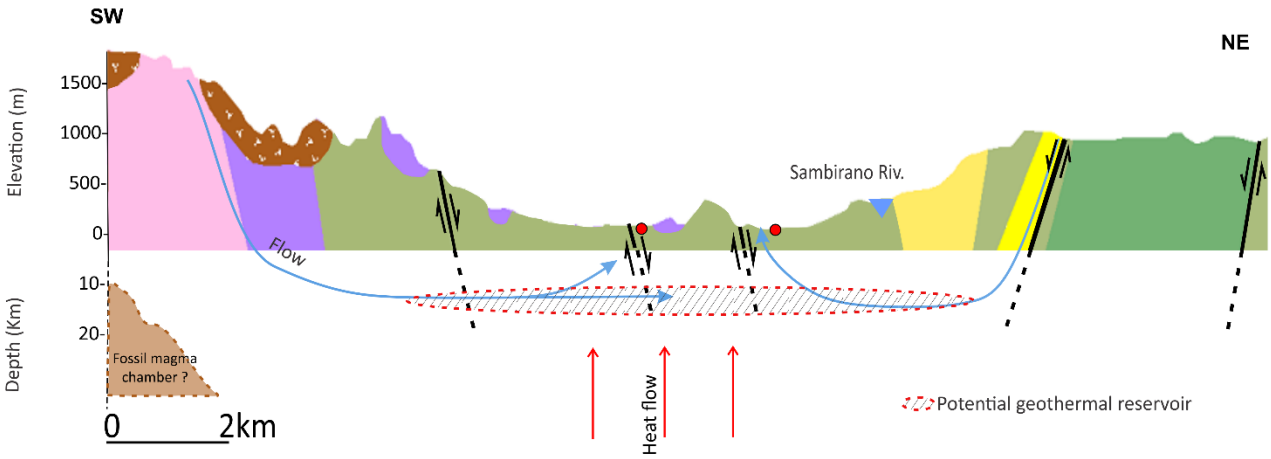


Figure 4: Conceptual geothermal model of Ambanja area in Sambirano graben (legends same as Figure 1c). Vertical scale of elevation profile is different from the depth's scale based on the structure of crust and uppermost mantle beneath Madagascar (Andriampenomanana et al., 2017)

5.3 Thermohydraulic properties

5.3 1 Hydraulic properties

Sedimentary rocks in the both areas have a mean value of porosity ranging from 0.7 to 8.7% (Table 1). Permian, Triassic sandstones and Eotriassic shale present the maximal value. The mean permeability of sedimentary rocks is around 8.0 mD (7.9×10^{-15} m^2) with the maximum value obtained in breccia 10.3 mD (1.0×10^{-14} m^2). For the basement rocks, the mean value of porosity ranges from 2.1 to 10.7%, while their permeability varies between 0.001 md (9.9×10^{-19} m^2) and 10.1 mD (1.0×10^{-14} m^2). The syenite intrusion has a porosity (<0.1) and a permeability below the detection limit (<0.001 mD) of the instruments used for measurements. The values correspond to the lowest permeability range observed in unfractured to fractured igneous and metamorphic rocks (Freeze & Cherry, 1979). However, secondary permeability due to faults and fractures is expected in the areas and could not be measured in the lab.

Table 1: Hydraulic property statistics for the different rock types

Rock type	Sedimentary				Metamorphic and igneous basement					Extrusive
Rock lithology	Permian-Trias Sandstone	Eotrias Shale	Breccia	*Quartz-barite vein	Ortho-gneiss	Micashist	Amphibolite	Para-gneiss	Syenite	Basalt
Porosity vol (%)	8.7	8.4	6.9	0.7	4.8	10.7	6.1	2.1	<0.1	1.1
Permeability (mD)										
Mean	**10.1**	**9.4**	**10.3**	**0.3**	**10.1**	**7.6**	**0.9**	**3.1**	<0.001	**0.5**
Maximum	28.5	22.1	18.1	1.3	12.0	20.8	1.7	8.6	<0.001	0.6
Minimum	1.4	4.0	8.1	0.7	9.6	4.2	0.3	0.5	<0.001	0.3
Standard deviation	4.2	6.29	3.74	0.3	0.7	3.7	0.9	3.3		0.1
Total number of measurements (N)	182	39	18	12	9	18	18	72	3	6
Number of samples (n)	18	5	2	3	3	2	2	14	1	2

*intrusive hydrothermal veins

5.3 2 Thermal properties

The thermal conductivity of the sediments rock samples from both areas varies between 2.5 and 4.9 W m^{-1} K^{-1}, while the basement rocks thermal conductivity ranges between 2.4 and 3.4 W m^{-1} K^{-1}. The micashist and syenite have a same mean value of 2.6 W m^{-1} K^{-1} and the minimal value is found in basalt formation with a mean of 2.4 W m^{-1} K^{-1}. The mean thermal diffusivity of all rocks varies from 1.1 to 2.4 × 10^{-6} m^2 s^{-1} and the heat capacity ranges between 2.0 and 2.6 MJ $K^{-1}m^{-3}$.

Table 2: Thermal property statistics of rocks from Ambilobe and Ambanja areas.

Rock type	Sedimentary				Metamorphic and igneous basement					Extrusive
Rock Lithology	Permian-Trias Sandstone	Eotrias Shale	Breccia	*Quartz barite vein	Ortho-gneiss	Micashist	Amphibolite	Para-Gneiss	Syenite	Basalt
Thermal conductivity ($Wm^{-1}K^{-1}$)										
Mean	**3.6**	**2.5**	**3.3**	**4.9**	**3.4**	**2.6**	**2.5**	**3.0**	**2.6**	**2.4**
Maximum	6.3	4.1	4.0	5.7	5.6	3.5	4.3	5.0	3.4	2.6
Minimum	2.7	1.3	2.7	3.9	2.6	1.8	1.6	1.7	1.9	2.2
G (%)	4.9	8.0	10.8	4.9	7.1	6.5	6.6	10.6	3.4	3.5
Thermal diffusivity ($10^{-6}m^2 s^{-1}$)										
Mean	**1.6**	**1.2**	**1.6**	**2.4**	**1.5**	**1.1**	**1.1**	**1.4**	**1.1**	**1.0**
Maximum	3.3	2.5	2.4	3.1	3.5	1.5	3.6	3.8	1.7	1.1
Minimum	1.0	0.4	1.2	1.9	1.0	0.9	0.6	0.6	0.8	0.9
Volumetric heat capacity ($MJK^{-1}m^{-3}$)										
Mean	**2.3**	**2.6**	**2.0**	**2.1**	**2.2**	**2.2**	**2.4**	**2.2**	**2.3**	**2.4**
Maximum	2.3	2.6	2.0	2.1	2.2	2.2	2.4	2.2	2.3	2.4
Minimum	2.6	3.1	1.7	2.2	2.1	1.9	1.6	1.7	2.1	2.5
Total number of measurements (N)	1661	490	254	472	186	139	577	1515	77	270
Number of samples (n)	18	5	2	3	3	2	4	14	1	2

*intrusive hydrothermal veins, G= standard deviation divided by mean (Popov et al., 2016)

5. DISCUSSION AND CONCLUSIONS

Geothermal systems of both areas of interest are associated with an extensional domain and referred to as the geothermal resource play (Moeck, 2014). Faults and fractures appear to be the dominant controls for fluid migration, bringing hot water toward the surface. The heat source is closely related to thinning of crust and Quaternary magmatic activities in the North region. Therefore, the present study combined with the results from the previous assessment conduct by Gunnlaugsson et al. (1981) allows to classify Ambilobe geothermal area mainly as a graben border-fault liquid-dominated moderate-temperature system whereas Ambanja geothermal area is defined as a fossil magmatic liquid-dominated moderate temperature system. Moreover, the characteristics of the geothermal system of Ambilobe are similar to the geothermal systems in western Great Basin in the Basin Range province in America where the majority of springs are found in a transtensional settings and with non-magmatic heat source (Faulds et al., 2010). The temperature of reservoirs in the western Great Basin is estimated from 150°C to 240°C (Faulds et al., 2010). Ambanja is more comparable to the western Turkey geothermal systems, which is associated to the Gedzi graben where heat flow varies from ~50 to 140 mW m^{-2} and has values exceeding ~100 mW m^{-2} (Yilmazer et al., 2010).

The first estimation of thermal and hydraulic properties of the rock units provided an initial evaluation and indication of the most interesting formation to host potential geothermal resources. The air permeability values given here should be taken with caution because the permeability was not corrected for Klinkenberg effect (Tanikawa & Shimamoto, 2009; Al-Jabri et al., 2015) which can overestimate the liquid permeability. Further permeability measurements made with a gas permeameter under varying pressure conditions will be subsequently performed. The mean range value of porosity of Permian and Triassic sandstones is comparable to the porosity recorded from Permian sandstones of Ripon formation from Karoo Basin in South Africa which is 0-3.7%, (Campbell et al., 2016). However, the permeability reported by these authors which is the order of magnitude of 0.01mD (1.2×10^{-17} m²) is relatively low when compared to those presented by this study. The Permian-Triassic sandstones and Precambrian orthogneiss have the highest thermal conductivity. The dominant heat transfer mechanism in these systems, which can be qualified as petrothermal, is expected to be heat conduction, except where permeability is enhanced by secondary features such has fractures that can allow advective heat transfer and appears to be the main factor controlling the occurrence of thermal springs.

The thermal and hydraulic properties measured in this study will be used to define thermofacies to better illustrate the impact of geothermal parameters, which enable the characterization of geothermal system and can help to develop numerical models of heat transfer and groundwater flow in order to better understand fluid path giving rise to hot springs.

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REFERENCES

Al-Jabri, R. A., Al-Maamari, R. S., & Wilson, O. B.: Klinkenberg-corrected gas permeability correlation for Shuaiba carbonate formation. *Journal of Petroleum Science and Engineering.* V.131 (2015).p. 172-176

American Petroleum Institute: Recommended practices for core analysis. Recommended Practice 40. Washington: API Publishing Services (1998).

Andriampenomanana, F., Nyblade, A. A., Wysession, M. E., Durrheim, R. J., Tilmann, F., Julià, J., Shore, P. J.: The structure of the crust and uppermost mantle beneath Madagascar, *Geophysical Journal International,* **210***,* (2017), 1525-1544.

Axelsson, G.: Conceptual models of geothermal systems–introduction. *Proceedings,* Short Course on Conceptual Modelling of Geothermal Systems, Santa Tecla, El Salvador, (2013).

Core Lab.: Portable probe permeameter operations manual. Core Laboratories, Tulsa, USA, (2016).

Coretest Systems. Automated permeameter-porosimeter operator's manual. Coretest Systems, Inc, Nevada, USA, (2017).

Cucciniello, C., Tucker, R., Jourdan, F., Melluso, L., & Morra, V.: The age and petrogenesis of alkaline magmatism in the Ampasindava Peninsula and Nosy Be archipelago, northern Madagascar, *Mineralogy and Petrology,* **110**, (2016), 309-331.

Cumming W.: Geothermal ressource Conceptual models using surface exploration data*. Proceeding,* 34th Workshop on Geothermal Reservoir Engineering*,* Stanford University, Stanford, CA (2009).

Dickson MH, Fenelli M. What is Geothermal Energy? Istituto de Geoscienze e Georisorse, CNR, Pisa, Italy, (2004)

Estrade, G.: Le complexe cénozoïque alcalin d'Ambohimirahavavy à Madagascar: origine, évolution et minéralisations en métaux rares*.* Ph.D thesis, Universite Toulouse III Paul Sabatier.(2014).

Estrade, G., Béziat, D., Salvi, S., Tiepolo, M., Paquette, J.-L., & Rakotovao, S.: Unusual evolution of silica-under- and -oversaturated alkaline rocks in the Cenozoic Ambohimirahavavy Complex (Madagascar): Mineralogical and geochemical evidence, *Lithos,* **206-207**, (2014), 361-383.

Freeze, R. A., & Cherry, J. A.: Groundwater. Englewood Cliffs, N.J.: Prentice-Hall (1979).

Gunnlaugsson, E., Arnorsson, S., & Matthiasson, M.: Madagascar-Reconnaissance survey for geothermal resources, Projet MAG/77/104, Contract 141/79 VIRKIR, Iceland, (1981).

Hambinintsoa, R. A. H., Ranaivoarisoa, A., & Blessent, D.: Hydrogeochemical Characterization of Thermomineral Waters in the Central Highlands of Madagascar. *UNESCO IGCP636,* Santiago (2017).

Hochstein, M. P.: Classification and assessment of geothermal resources. *in : Dickson MH and Fanelli M., eds., Small geothermal resources: A guide to development and utilization,* UNITAR, New York*,* .(1990), 31-59.

Lardeaux, J. M., Martelat, J. E., Nicollet, C., Pili, E., Rakotondrazafy, R., & Cardon, H.: Metamorphism and Tectonics in Southern Madagascar: An Overview, *Gondwana Research.* **2**, (1999), 355-362.

Moeck, I. S.: Catalog of geothermal play types based on geologic controls, *Renewable and Sustainable Energy Reviews,* **37**, (2014), 867-882.

Popov Y.A., Pribnow D.F.C., Sass J.H., Williams C.F. & Burkhardt H.: Characterization of rock thermal conductivity by high-resolution optical scanning. *Geothermics*, 2**8**, (1999), 253-276.

Popov, Y., Beardsmore, G., Clauser, C., & Roy, S.: ISRM suggested methods for determining thermal properties of rocks from laboratory tests at atmospheric pressure, *Rock Mechanics and Rock Engineering,* **49**, (2016), 4179-4207.

Pratt, M. J., Wysession, M. E., Aleqabi, G., Wiens, D. A., Nyblade, A. A., Shore, P., Tucker, R. D.: Shear velocity structure of the crust and upper mantle of Madagascar derived from surface wave tomography, *Earth and Planetary Science Letters,* **458**, (2017), 405-417.

Rajaobelison, M., Raymond, J., Malo, M., & Dezayes, C.: Classification of geothermal systems in Madagascar. *Geothermal Energy.* V.8 (2020).p. 22

Rindraharisaona, E. J., Tilmann, F., Yuan, X., Rumpker, G., Giese, J., Rambolamanana, G., & Barruol, G.: Crustal structure of southern Madagascar from receiver functions and ambient noise correlation: Implications for crustal evolution, *Geophysical Research-Solid Earth,* **122**, (2017), 1179-1197.

Roig, J.Y., Tucker, R.D., Delor, C., Peters, S.G., Théveniaut, H., Carte géologique de la République de Madagascar à 1/1 000 000. Ministère des Mines, PGRM, Antananarivo, République de Madagascar, 1 color sheet, (2012).

Rossi, G.: Quelques aspects d'une haute montagne tropicale : le massif du Tsaratanana (Madagascar), In: Revue de géographie alpine, tome 68, n°2, (1980), 153-172.

Sarazin, G., Michard, G., & Pastor, L.: Geochemical study of the geothermal field of Antsirabe (Madagascar), *Geochemical Journal*, **20** (1986), 41-50.

Sass, I., & Götz, A. E.: Geothermal reservoir characterization: a thermofacies concept, *Terra Nova,* **24**, (2012), 142-147.

Tanikawa, W., & Shimamoto, T.: Comparison of Klinkenberg-corrected gas permeability and water permeability in sedimentary rocks. International Journal of Rock Mechanics and Mining Sciences, **46(2)**, (2009), 229–238.

Thomas, B., Waele, B., Schofield, D. I., Goodenough, K., Horstwood, M., Tucker, R., Randriamananjara, T.: Geological evolution of the Neoproterozoic Bemarivo Belt, northern Madagascar. Precambrian Research, **172** (2009), 279-300.

Tucker, R., Roig, J. Y., Moine, B., Delor, C., & Peters, S. G.: A geological synthesis of the Precambrian shield in Madagascar, *African Earth Sciences*, **94** (2014), 9-30.

Wysession, M., Pratt, M., Andriampenomanana Ny Ony, F., Tsiriandrimanana, R., Nyblade, A., Aleqabi, G., Rambolamanana, G.: The Lithospheric Structure of Madagascar*,* AGU Fall Meeting Abstracts, San Fransisco, (2016).

Yilmazer, S., Pasvanoğlu, S., & Vural, S.: The Relation of Geothermal Resources with Young Tectonics in the Gediz Graben (West Anatolia, Turkey) and Their Hydrogeochemical Analyses, *Proceedings,* World Geothermal Congress, Bali Indonesia*,* (2010)