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► **To cite this version:**

M. Rajaobelison, J. Raymond, M. Malo, Chrystel Dezayes, S. Larmagnat. Understanding heat transfer along extensional faults: The case of the Ambilobe and Ambanja geothermal systems of Madagascar. *Geothermics*, 2022, 104, pp.102455. 10.1016/j.geothermics.2022.102455 . hal-03694776

HAL Id: hal-03694776

<https://brgm.hal.science/hal-03694776v1>

Submitted on 13 Jan 2023

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1 **Understanding heat transfer along extensional faults: the case of the Ambilobe and**
2 **Ambanja geothermal systems of Madagascar**

3

4 **M. Rajaobelison**

5 INRS – Institut national de la recherche scientifique

6 490, rue de la Couronne. Québec (Québec) G1K 9A9 Canada

7 Miora.Mirah.Rajaobelison@inrs.ca

8 ORCID : 0000- 0002- 8125-5210

9 Corresponding author

10 **J. Raymond**

11 INRS – Institut national de la recherche scientifique

12 490, rue de la Couronne. Québec (Québec) G1K 9A9 Canada

13 ORCID: 0000-0001-7596-2800

14 **M. Malo**

15 INRS – Institut national de la recherche scientifique

16 490, rue de la Couronne. Québec (Québec) G1K 9A9 Canada

17 ORCID: 0000-0001-5941-9736

18 **C. Dezayes**

19 BRGM – Bureau de recherches géologiques et minières, 3 Avenue Claude Guillemin,

20 45100 Orléans, France

21 ORCID: 0000-0001-7813-359X

22 **S. Larmagnat**

23 Geological Survey of Canada, 490, rue de la Couronne, Québec, QC G1K 9A9, Canada

24 ORCID:

25 **Keywords:** Energy; Geothermal; Heat transfer; Faults, Numerical modeling, Madagascar

26 **Abstract**

27 Understanding the role of faults where forced convective heat transfer is the dominant
28 mechanism giving rise to hot springs is critical in geothermal exploration in extensional
29 environments. This study uses two-dimensional models of coupled fluid flow and heat
30 transfer along cross-sections perpendicular to faults and the regional topography to identify
31 favorable fault conditions for geothermal system development in northern Madagascar.
32 Structural data collected at surface were used to define fault scenarios and simulate the
33 ascension of hot fluids to reproduce hot spring temperatures in the Ambilobe normal fault
34 zone area and the Ambanja graben structure. Fault dips facing topography- driven
35 groundwater flow was shown to be favorable, and hot spring temperatures could be
36 reproduced when the fault permeability was $>10^{-14}$ m². Faults located in a discharge zone
37 near a river were the most favorable for fluid ascension, regardless of their dip.
38 Constraining the model with a basal heat flow between 90 and 148 mWm⁻² at a depth of
39 10 km allowed the reservoir temperature to reach 150–200 °C at depths of 2 km or
40 shallower along favorable faults.

41 **1. Introduction**

42 Economic activity in the northern region of Madagascar relies on export products such as
43 vanilla, cocoa and coffee that are grown and transformed locally. Madagascar is one of the
44 largest vanilla exporters in the world (UNComtrade, 2018). The energy used to transform
45 these products relies heavily on fossil fuels and wood. Off-grid communities, mainly in

46 remote areas, use traditional biomass such as firewood and charcoal as their main source
47 of energy, inducing deforestation and water resource degradation, along with biodiversity
48 and soil loss, as has already happened in many Madagascar communities. Renewable
49 sources, such as geothermal energy, are expected to play a more prominent role in future
50 energy production.

51 Ambilobe and Ambanja, two areas in northern Madagascar, have been characterized for
52 their geothermal potential and respectively classified as a graben border-fault liquid-
53 dominated moderate-temperature system and a fossil magmatic liquid-dominated
54 moderate-temperature system (Rajaobelison et al. 2020). In this classification scheme
55 based on the extensional type, the fault and lithologic-diagenetic characteristics affecting
56 porosity are thought to control formation permeability. As reported by Rajaobelison et al.
57 (2020), the average matrix permeability of fracture-free rocks in these two areas was
58 evaluated between 10^{-13} and 10^{-18} m², which is low, while the average porosity is ~5.7 %,
59 which is low or poor (5–10 %) according to Levorsen and Berry (1967); Tiab and
60 Donaldson (2016). However, this matrix permeability has to be considered the lower bound
61 of formation permeability as fractures are common in such an extensional tectonic setting.
62 The occurrence of thermal springs along a major fault zone in Ambilobe and a graben
63 structure in Ambanja confirms that advective heat transfer can take place within fractured
64 rocks (Rajaobelison et al. 2020). The equilibrium formation temperature at depth,
65 estimated using chemical geothermometers (Gunnlaugsson et al. 1981), ranges from 140
66 to 200 °C, high enough to be used for scalding vanilla beans (~60 °C), heating greenhouses
67 (> 40 °C; Lindal 1973), and generating electricity (> 80 °C; Grasby et al. 2011; Tomarov
68 and Shipkov 2017). Fluids from geothermal sources with temperatures below 120 °C can

69 be used to generate electricity using an optimized Organic Rankine Cycle (e.g. Chagnon-
70 Lessard et al. 2020; Liu et al. 2017; Shi and Pan 2019).

71 No exploration boreholes have been drilled in northern Madagascar, so the optimal depth
72 for finding geothermal sources remains unknown, as do the geothermal gradient and heat
73 flux density. Previous work classified geothermal play types and evaluated rock thermo-
74 hydraulic properties from surface outcrops to better understand heat transfer mechanisms
75 at depth (Rajaobelison et al. 2020; Rajaobelison et al. 2021). Crustal-scale faults have been
76 identified as potential targets for geothermal exploration, but further work is needed to
77 better understand their role in the subsurface heat transfer mechanisms that control the
78 depth and extent of geothermal sources. Fault influence must be taken into account when
79 exploring geothermal energy sources, especially the influence of the large-scale faults
80 identified by surface mapping and shown on the geological maps of Madagascar by Roig
81 et al. (2012) and Tucker et al. (2014). Therefore, numerical modeling was used to simulate
82 groundwater flow and heat transfer according to various fault scenarios affecting the
83 geothermal energy sources associated with petrothermal systems in this extensional
84 domain of Madagascar.

85 Numerical modeling has been previously used to simulate the depth distribution of
86 temperature to better understand fractured geothermal reservoirs (e.g. Bakhsh et al. 2016;
87 Corbel et al. 2012; Hao et al. 2012; Holzbrecher et al. 2010). Faults that serve as conduits
88 and increase permeability (e.g. Brogi et al. 2021; Ferrill et al. 2004; Liotta et al. 2021;
89 Zucchi 2020) are important targets for geothermal resource exploration, but if they act as
90 barriers and decrease permeability (e.g. Gibson 1998), they can compartmentalize the
91 reservoirs, making it challenging to access and exploit the resource (Loveless et al. 2014).

92 Furthermore, the prediction and modeling of coupled fluid flow and heat transfer processes
93 in naturally fractured rock systems are critical components in energy recovery analysis
94 (Hao et al. 2012). In addition, numerical modeling of hydrothermal systems has often been
95 used to explain hot spring occurrences and explore their controlling factors (e.g. Bense et
96 al. 2008; Forster and Smith 1989; Guillou-Frottier et al. 2013; López and Smith 1995;
97 Magri et al. 2016; Taillefer et al. 2018; Volpi et al. 2017). Recently, Szijártó et al. (2019);
98 and Szijártó et al. (2021) used numerical modeling to investigate the conditions that can
99 induce and favor forced convection. Moreno et al. (2018) demonstrated that the orientation
100 of the fault dip in relation to the direction of regional groundwater flow driven by
101 topography could affect groundwater uprise and, consequently, hot spring occurrence and
102 temperature.

103 This study aims to understand the role of faults on forced convective heat transfer that gave
104 rise to hot springs in northern Madagascar, thereby providing fundamental knowledge that
105 can be used to improve geothermal exploration concepts. Our working hypothesis is that
106 fault dip at depth, which is currently unknown, can affect the rise of hot fluids. We
107 developed numerical groundwater flow and heat transfer models to reproduce the near-
108 surface temperatures of hot springs since this is the only information available in the area
109 to validate simulations. We present innovative concepts supported by 2D numerical
110 simulations of deep subsurface temperature in northern Madagascar that test seven base-
111 case fault scenarios or hypotheses. We identified fault characteristics that favored the
112 formation of geothermal energy sources to help advance geothermal exploration.

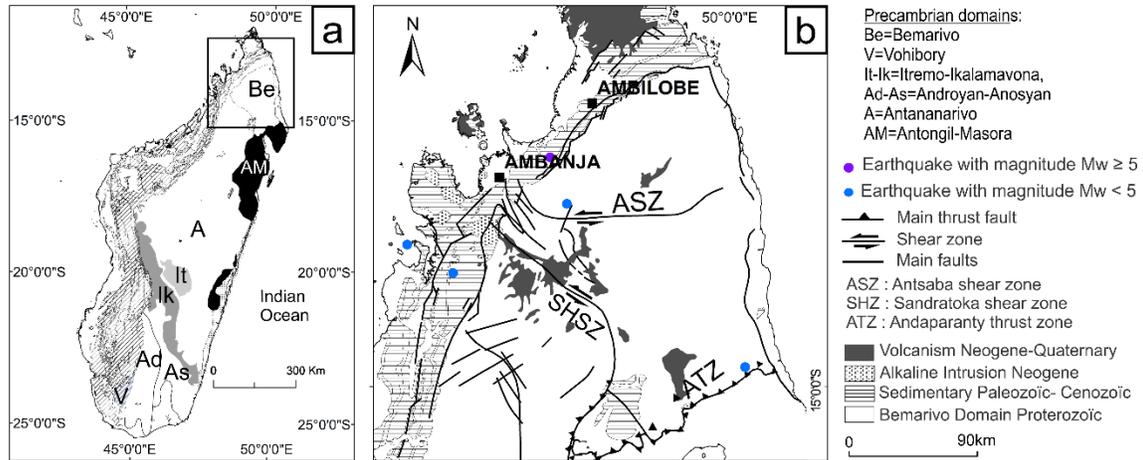
113 2. Geological setting and geothermal context

114 2.1 Tectonic framework and regional fault system

115 The Bemarivo domain, one of the six geodynamic domains forming the Madagascar
116 Shield, underlies the northern end of Madagascar, where the geothermal areas of interest,
117 Ambilobe and Ambanja, are situated. This Neoproterozoic domain is composed of
118 Cryogenian igneous rocks, with a cryptic Paleoproterozoic basement accreted to the
119 Greater Dharwar Craton in latest Ediacaran to earliest Cambrian time, 0.53–0.51 Ga
120 (Tucker et al. 2014). The Bemarivo domain has been interpreted as an assemblage of two
121 juvenile arc terranes (Figure 1) with estimated ages between c. 750 and 720 Ma (Thomas
122 et al. 2009). The east-west Antsaba shear zone, a major ductile structure, separates these
123 northern and southern terranes. The shear zone, about 15 km across at its widest location
124 in the west (Thomas et al. 2009), is interpreted as a subduction zone along which the
125 northern and southern terranes were amalgamated (Armistead et al. 2019). Contrary to the
126 suggestion of Thomas et al. (2009) and Armistead et al. (2019), the Bemarivo domain is
127 considered a single domain based on the lithostratigraphy and ages reported in Tucker et
128 al. (2014).

129 Mesozoic and younger movements along the Antsaba shear zone produced a variety of
130 faults and dykes related to the break-up of Gondwana and rifting in the Mozambique
131 Channel. The extensional phases from Triassic to Jurassic (Karoo rift) gave rise to NNE-
132 SSW and NNW-SSE faults, whereas faults generally striking N140°-N160° were
133 transformed into wrench faults with dextral movement during Jurassic-upper Cretaceous
134 times, coherent with the development of the Davie Ridge (Lardeaux et al. 1999). Numerous
135 NE-SW and NW-SE faults are consistent with the identified faults and the regional Plio-

136 Quaternary direction of extension (N65°E to N85°E) observed in the volcanic region of
137 Montagne d'Ambre, in the extreme north of Madagascar (Chorowicz et al. 1997)



139 **Figure 1** Simplified geological maps showing a) the six main geodynamic
140 Precambrian domains that form the Madagascar Shield (modified from De Waele et al.
141 2011; Tucker et al. 2014), b) and a close-up of the tectonic framework of the Bemarivo
142 domain in northern Madagascar (modified from Armistead et al. 2019; Thomas et al. 2009),
143 enclosing the Ambilobe and Ambanja study areas.

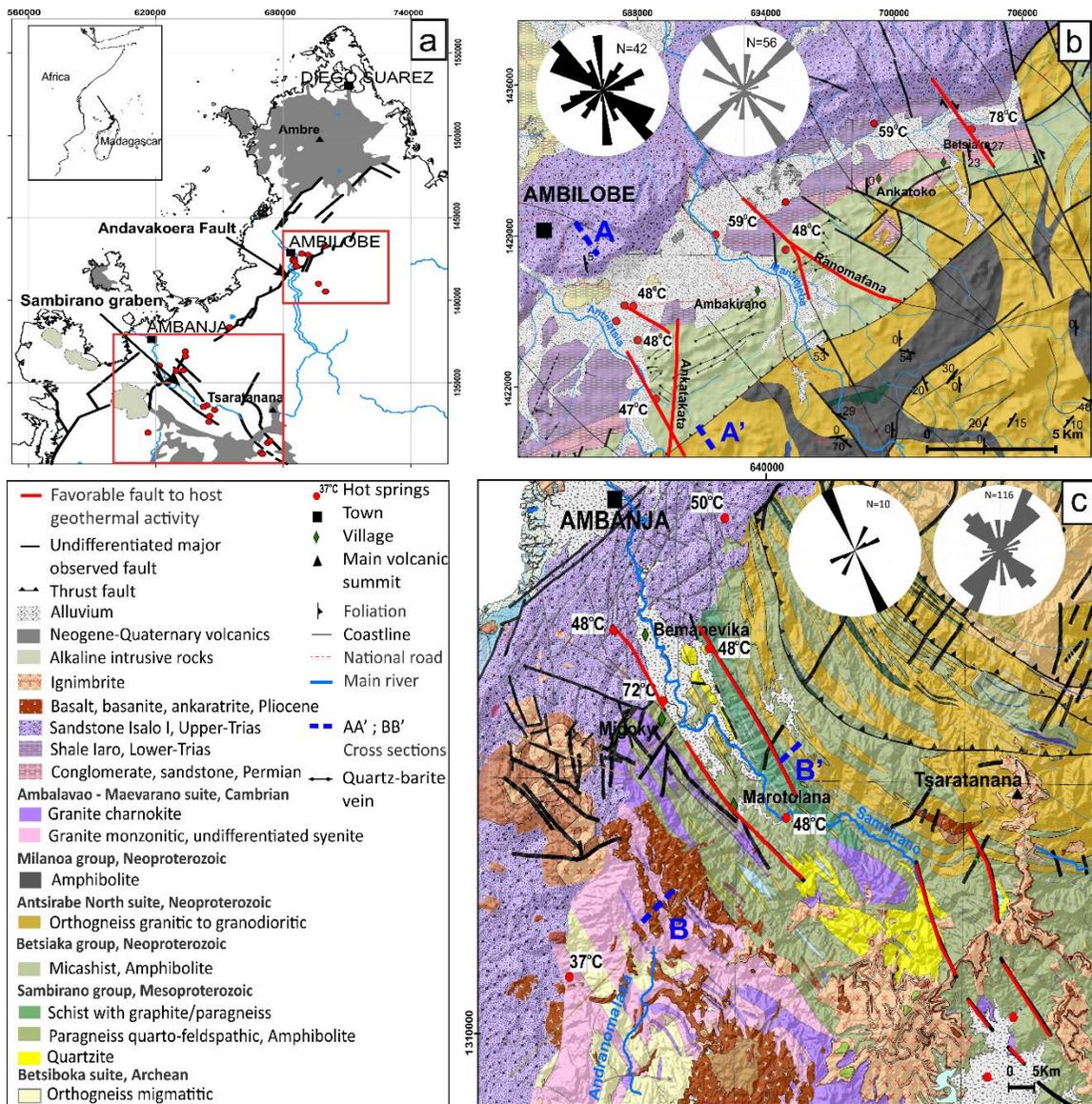
144 The Ambilobe area is located in the Andavakoera fault zone, a major NE-SW normal fault
145 delineating the contact between sedimentary sequences and basement rocks of the northern
146 Bemarivo domain. Numerous undifferentiated NW-SE faults and NW-SE strike-slip faults
147 with dextral or sinistral movements can be seen on the geological map (Figure 2b) and in
148 the field (Figure 3a). The strike-slip faults include the faults near the Betsiaka hot springs
149 and undifferentiated normal faults of Ranomafana and Ankatakata (Figure 2b). The main
150 fault and fracture systems are dominated by NNW-SSE, NE-SW and N-S orientations.

151 Fracture orientations from field measurements and fault orientations from geological map
152 are shown on the rose diagram of Figure 2b.

153 The Ambanja area is located in the graben structure in the Proterozoic basement units of
154 the southern terrane of the Bemarivo domain. The graben is oriented NW-SE, and its
155 average width is 4 km. The main faults and fractures dominantly strike NNW-SSE. The
156 rose diagrams of fracture orientations from field measurements as well as the faults
157 orientations from the geological map are shown on Figure 2c. Some metric fractures were
158 observed at the outcrop scale (Figure 3b)

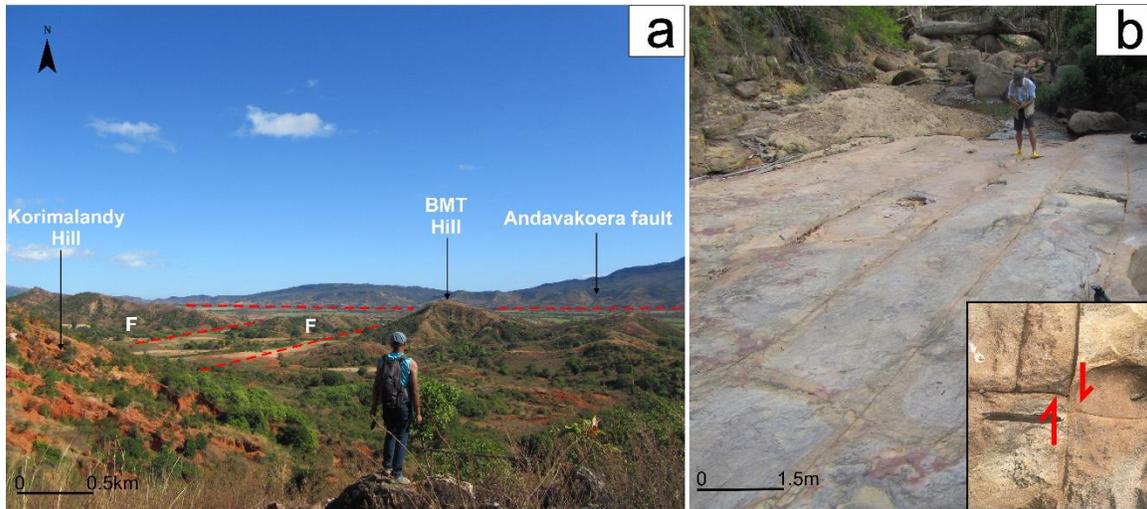
159 **2.2 Favorable structural patterns**

160 In a comprehensive inventory of the structural settings of geothermal systems in the Great
161 Basin region of western USA, Faulds and Hinz (2015) identified the most favorable
162 dominant faulting patterns to host geothermal activity in the extensional to transtensional
163 terranes, and more specifically in areas where the bulk of the geothermal resources are
164 likely hidden. Applying the same principles to the Ambilobe and Ambanja areas, the
165 identified favorable fault structures are: 1) major normal fault segments, i.e., near the
166 displacement maxima of the NE-SW Andavakoera fault and the NW-SE fault-borders of
167 the Ambanja graben structure intersections between two normal faults (Figure 2b and 2c),
168 and 2) or between normal faults and transverse oblique-slip faults (Figure 2c).



169

170 **Figure 2** (a) Location of the Ambilobe and Ambanja geothermal areas. (b) and (c)
 171 Detailed geology of each area (modified from Roig et al. 2012). The rose diagrams
 172 illustrate the major fracture trends (in black) established from field data collected in 2018
 173 and the major faults trends (in grey) established from the map data of Roig et al. (2012).



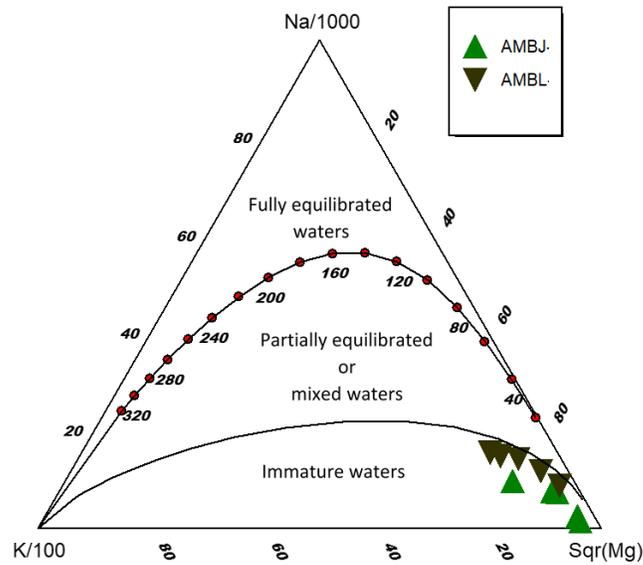
174

175 **Figure 3:** a) Field view of the Andavakoera fault line and its conjugated faults (F). b)
176 Metric fractures in the Ambanja sandstone formation with close-up illustrating fracture
177 movements.

178 At the surface, hot springs reach a temperature varying from 50 to 72 °C in both areas
179 (Besairie 1959; Gunnlaugsson et al. 1981). Waters from the hot springs have high Mg
180 concentrations and fall into the immature field on the ternary Na-K-Mg diagram of
181 Giggenbach (1988), indicating dilution of the geothermal fluid along its path to the surface
182 (Figure 4). The geothermal fluid thus mixed with meteoric and shallow groundwater.

183 Using chemical geothermometers (Gunnlaugsson et al. 1981) and the Giggenbah diagram
184 (Figure 4), the reservoir temperatures in the Ambilobe and Ambanja areas are expected to
185 be 140 and 200 °C, respectively.

186
187
188
189
190
191
192



193 **Figure 4:** Chemical composition of waters from the Ambilobe (AMBL) and Ambanja
194 (AMBJ) hot springs plotted on a ternary Na-K-Mg diagram (Giggenbach 1988). The Na,
195 K, Mg concentrations were reported in Gunnlaugsson et al. (1981).

196

2.3 Lithosphere structure and geological formations

197 In the Bemarivo domain, the Moho is at a depth of 33 km (Andriampenomanana et al.
198 2017). The thickness of the upper crust is up to 20.5 km, and its composition is assumed to
199 be primarily paragneiss and sedimentary rocks which have an average thickness of 4 km.
200 The lower crust is assumed to be composed of mafic rocks with an average thickness of
201 12.5 km.

202 The geological formations of the Ambilobe and Ambanja areas and their thermo-hydraulic
203 properties have been described in Rajaobelison et al. (2020); and Rajaobelison et al. (2021).
204 The Permo-Triassic sedimentary rocks of the Ambilobe Basin, overlying the Proterozoic
205 basement of the Bemarivo domain, are the main formations in the Ambilobe area. The

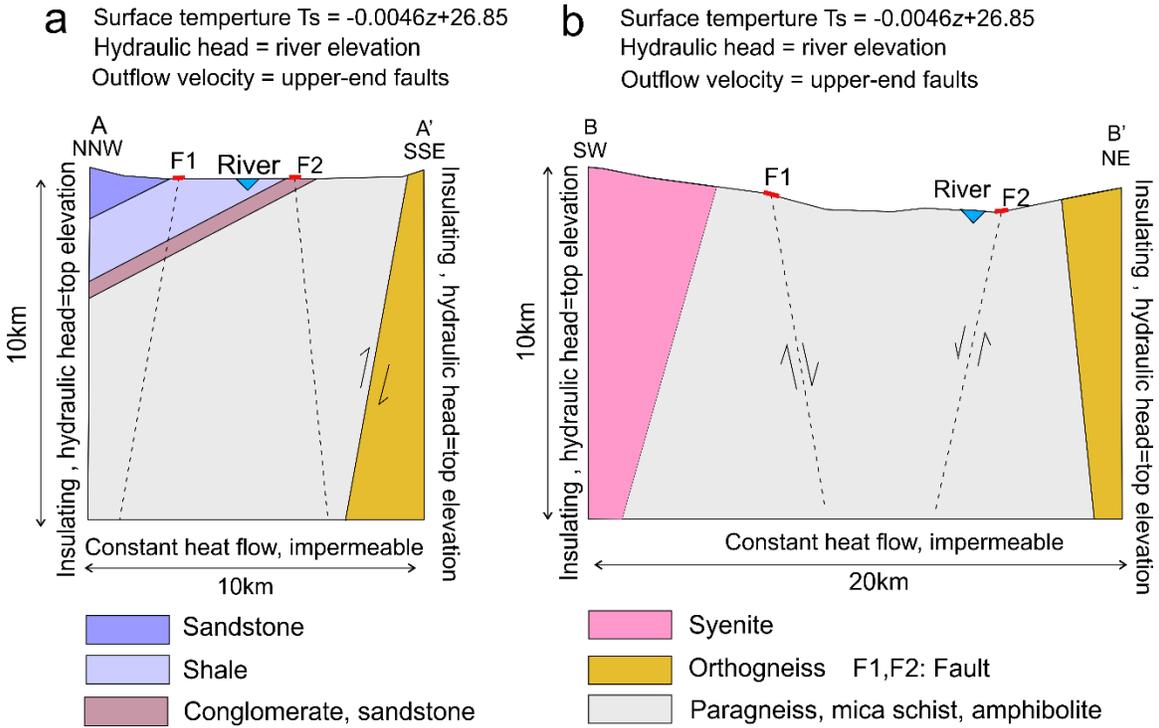
206 Proterozoic basement rocks of the Bemarivo domain are the only geological formations
207 exposed in the Ambanja area (Figure 2).

208 3. Development numerical heat transfer model

209 3.1 Conceptual model and assumptions

210 The geometry of the models (Figure 5) accounts for the topography on NNW-SSE (AA')
211 and NE-SW (BB') cross-sections (Figures 2b and 2c) that pass through, respectively, the
212 Andavakoera normal fault zone at the contact between sedimentary sequences and
213 basement rocks in the Ambilobe area, and the graben structure in the Ambanja area. The
214 dominant sedimentary and basement units have been considered in the models. The cross-
215 sections are perpendicular to the main undifferentiated faults observed near hot spring
216 occurrences. The faults represented in the models are N010° Ankatakata post-Triassic
217 normal oblique-slip faults in the Ambilobe area and N140° border faults in the Ambanja
218 graben (Figures 2b and 2c). These faults appear on the geological map of Madagascar
219 produced by Roig et al. (2012).

220 Different modeling scenarios were defined to investigate the influence of fault dip on
221 groundwater flow and heat transfer processes (Table 1). The dips in the two models range
222 from 60° to 85° since dips from 60° to vertical have been shown to cause variations in the
223 pressure and temperature of subsurface fluids (Cherubini et al. 2013). These modeling
224 scenarios were based on the geological maps of Ambanja and Ambilobe, although many
225 uncertainties remain about fault dip and down-dip continuity at depth, which justifies the
226 use of various scenarios. The models simulate the potential temperature distribution for the
227 Ambilobe and Ambanja geothermal areas according to fault dip influence.



229

230 **Figure 5:** Geometry and boundary conditions of the 2D numerical model based on the
 231 geological cross-sections (AA') and (BB') in Figure 2, representing a) the Andavakoera
 232 normal fault zone at the basement-sediment contact in the Ambilobe area, and b) the
 233 Ambanja graben.

234

Area	Faults	Dip	Scenario
Ambilobe	F1; F2	No fault	0
		70° NW; 85° SE	1
		60° NW; 60° SE	2
		80° SE; 75° SE	3
		80° NW; 85° NW	4
Ambanja	F1; F2	No fault	0
		80° SW; 80° NE	1
		75° NE; 80° NE	2
		75° NW; 80° NW	3

235

3.2 Governing equations

236 The models were developed using the subsurface flow module with a finite element method
 237 in the COMSOL Multiphysics software. The module couples groundwater flow simulated
 238 with Darcy's law and heat transfer in porous media. This made it possible to simulate
 239 forced convective heat transfer, which occurs along major faults where the host rock is
 240 considered an equivalent porous medium. Steady-state flow and heat transfer were
 241 numerically resolved according to the partial differential equation 1 and the input
 242 parameters summarized in Table 2. Sedimentary rocks and granitic and paragneiss
 243 basement rocks were considered low-permeability 2D units using the equivalent porous
 244 medium, where fluids can circulate. Faults are discrete 1D linear elements superposed on
 245 the 2D porous medium, where flow and heat transfer are solved simultaneously. Coupling
 246 between heat transfer and fluid motion occurs through the velocity field.

$$247 \quad \lambda_b \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right) - \rho_f c_f \left(u_x \frac{\partial T}{\partial x} + u_z \frac{\partial T}{\partial z} \right) + A = 0 \quad (1)$$

248 where λ_b ($\text{W m}^{-1} \text{K}^{-1}$) is the bulk thermal conductivity; T ($^{\circ}\text{C}$) is absolute
 249 temperature; u (m s^{-1}) is the velocity vector determined from simulations of fluid flow
 250 quantified with Darcy's law, ρ_f (kg m^{-3}) is the density of the fluid, c_f ($\text{J kg}^{-1} \text{K}^{-1}$) is the heat
 251 capacity of the fluid, and A (10^{-6}W m^{-3}) is the radiogenic heat production.

252

3.3 Geometry and subsurface properties

253

3.3.1. Geometry

254

- Ambilobe

255

The model has a width of 10 km and a depth of 10 km (Figure 5a). The sedimentary units

256

dip 20-30° to the NE. Table 2 details the material properties of the 5 lithological domains.

257

The reverse fault F marks the contact between the mica schist and orthogneiss formations,

258

and F1 and F2 are the mains faults represented in the models.

259

- Ambanja

260

The model has a rectangular geometry 20 km wide and 10 km deep (Figure 5b). Table 2

261

details the material properties of the 3 lithological domains. The properties of the border

262

faults of the graben, represented by F1 and F2, are also included in the table.

263

3.3.2. Thermohydraulic properties and internal heat

264

generation

265

The thermohydraulic properties of the model units were based on average properties

266

measured in the laboratory for each geological formation reported by Rajaobelison et al.

267

(2021), as summarized in Table 2. They are assumed to be constant with depth. Porosity \emptyset

268

and permeability k (m^2) were evaluated with transient measurements using the combined

269

AP-608 gas permeameter–porosimeter from Core Test Systems with nitrogen as the gas

270

source. The average bulk density ρ ($kg\ m^{-3}$) was obtained from porosity assessments.

Table 2 Model input parameters

Parameter	Value						Unit	Reference
Area	Ambilobe							
Formation	Sediments			Basement		Ambanja Basement		
Geological Units	Permian Sandstone	Eo Triassic shale	Triassic sandstone	Mica Shist Amphibolite	Ortho-gneiss	Syenite	Para-gneiss	
Mean ϕ	0.07	0.08	0.07	0.11	0.05	0.001	0.02	Fractional
Mean k	1.4×10^{-13}	1.0×10^{-17}	1.0×10^{-16}	1.0×10^{-15}	1.0×10^{-16}	1.0×10^{-18}	1.0×10^{-15}	m ²
Mean λ	3.6	2.5	3.5	2.6	3.4	2.6	2.7	W m ⁻¹ .K ⁻¹
Mean ρ	2542	2382	2628	2735	2678	2700	2678	kg.m ⁻³
Mean c	904	875	919	879	846	875	830	J kg ⁻¹ K ⁻¹
Mean A	1.14	0.72	1.25	0.58	0.38	1.35	0.38	10^{-6} W m ⁻³
Thickness Model	4			6		10		km
Depth of crust	33						km	Andriampenomanana et al. (2017)
Upper Crust (UC)	20.5						km	
Lower Crust (LC)	12.5						km	
Mean A (UC)	1.5						10^{-6} W m ⁻³	Horton et al. (2016)
Mean A (LC)	0.72						10^{-6} W m ⁻³	
A - Total Crust	1.2						10^{-6} W m ⁻³	
Fault Properties	F1; F2							
Aperture	Min.			Mean		Max.		m
D_f	250×10^{-6}			1.1×10^{-3}		2×10^{-3}		
Permeability	10^{-14}			10^{-10}		10^{-7}		
k_f							m ²	Current study

271 λ =thermal conductivity, ρ = density, c = heat capacity, A = radiogenic heat production

272 Transient thermal conductivity λ ($\text{Wm}^{-1} \text{K}^{-1}$) and diffusivity α ($\text{m}^2 \text{s}^{-1}$) were measured with
273 the optical scanning method using an infrared scanner developed by LGM Lippmann. The
274 heat capacity, c ($\text{J kg}^{-1} \text{K}^{-1}$), was deduced from the thermal conductivity and thermal
275 diffusivity assessment (Popov et al. 2016; Popov et al. 1999).

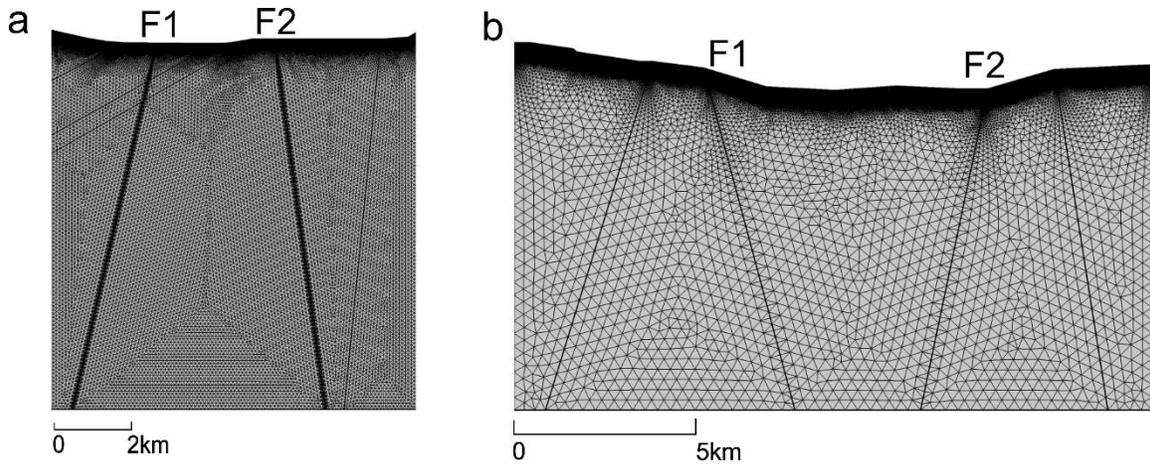
276 The internal radiogenic heat generation (A ; 10^{-6}W m^{-3}) for each rock presented in Table 2
277 was estimated from the concentration of the radiogenic elements U, Th and K, as reported
278 in Rajaobelison et al. (2021).

279 **3.3.3. Fault properties**

280 This study assumed fault aperture and permeability from $250 \mu\text{m}$ to 0.2cm and from 10^{-14}
281 to 10^{-7}m^2 , respectively (Table 2). These ranges are based on the literature, taken from
282 various in-situ hydraulic tests performed at geothermal sites (e.g. Holzbecher et al. 2011;
283 Jeong et al. 2001) and examples from numerical simulation studies of groundwater flow in
284 discrete fracture models (e.g. Bisdorn et al. 2016; Guillou-Frottier et al. 2013). The
285 minimum fault aperture range corresponds to that observed under a normal stress of
286 20Mpa in a laboratory experiment and which validated the cubic law for laminar flow of
287 fluids through open fractures (Witherspoon et al. 1980)

288 **3.4 Mesh**

289 Refinement of the mesh increases from bottom to top and close to the faults to avoid
290 convergence problems. These locations require more accuracy due to large flow and
291 temperature contrasts (Figure 6). A non-structured mesh with triangular elements was used,
292 and the mesh statistics are summarized in Table 3.



293

294 **Figure 6** Finite element mesh of the 2D numerical models for a) the Andavakoera
 295 normal fault zone at the basement-sediment contact in the Ambilobe area, and b) the
 296 Ambanja graben.

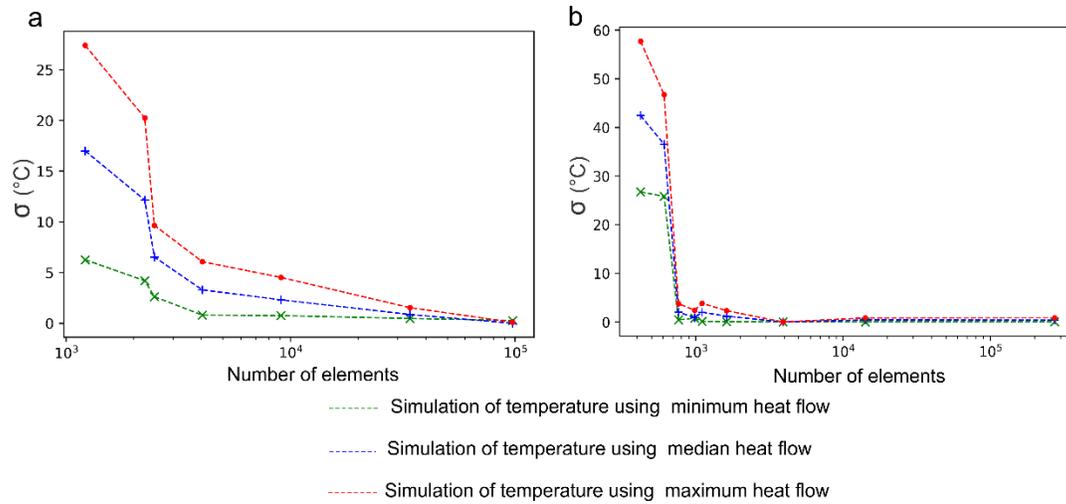
Table 3 Mesh statistics of Ambilobe and Ambanja 2D models

	Ambilobe	Ambanja	Unit
Number of element	101 672	274 403	
Maximum element size	104	404	m
Minimum element size	0.208	0.404	m
Nodes	49 506	137 998	

297 A mesh convergence study was undertaken to verify that the temperature solution is
 298 independent of the element size; i.e., a chosen cutline was sampled uniformly from the
 299 models at different mesh sizes. The parameter σ was then computed according to equation
 300 2:

$$301 \quad \sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (\Delta T_i)^2} \quad (2)$$

302 where N is the sample number, ΔT_i is the temperature variation at depth $x_i=(i-1)D/N-1$ along
 303 the chosen cutline where the mesh size of the model is refined. Here, D is the depth of the
 304 model. It demonstrated that a stable solution was obtained above 10^4 elements with a
 305 difference of about 1°C or less (Figure 7).



306

307 **Figure 7** Mesh convergence study for the a) Ambilobe and b) Ambanja models.

308

3.5 Boundary conditions

309

3.5.1 Groundwater flow conditions

310 Topography-driven groundwater flow affecting forced convection was reproduced by
 311 imposing lateral flow boundary conditions (López and Smith 1995; Smith and Chapman
 312 1983; Tóth 2009; Woodbury and Smith 1985). Without any information about the water
 313 table level, the lateral boundaries of the model are assigned a constant hydraulic head equal
 314 to the topographic elevation (Figure 5). Each segment representing a river in the model
 315 valley is also assigned a constant hydraulic head value equal to its nodal elevation. An
 316 outflow boundary was assigned at the upper-end of the faults to allow fluids to exit at the
 317 upper-end of the faults. The base of the models was assumed impermeable.

318

3.5.2 Heat transfer conditions

319 A constant temperature was specified at the surface of the models and assumed to be a
 320 linear function of the altitude. Equation 3 establishes the relationship between the surface
 321 temperature (T_s) and altitude (z):

$$322 \quad T_s = -0.0046z + 26.85 \quad (3)$$

323 where -0.0046 and 26.85 °C are constants determined from average annual temperatures
 324 measured at four meteorological stations in Madagascar: Antsiranana, Mahajanga,
 325 Antananarivo and Tolagnaro (Table 4; Stalenberg et al. 2018).

Table 4 Data from selected meteorological stations in Madagascar

Station	Antsiranana	Mahajanga	Antananarivo	Tolagnaro
Altitude (m)	105	27	1268	22
Average annual temperature (°C)	24.7	27	19.5	24

326 The lower boundary of the models, at a depth of 10 km, was assigned a second type
 327 condition of constant heat flow (Table 5), defined according to the Curie point depth (CPD;
 328 Tanaka et al. 1999) and the internal heat generation in the crust. Heat flow at the CPD
 329 (Q_{CDP} , mWm^2) was initially calculated using equation 4, which takes into account the
 330 surface ($T_0 = 20$ °C) and Curie ($T_{CDP} = 580$ °C) temperatures:

$$331 \quad Q_{cpd} = \lambda \frac{T_{CPD} - T_0}{Z_{CPD}} - A \frac{Z_{CPD}}{2} \quad (4)$$

332 where A (10^{-6} W m^{-3}) is the average heat generation due to the radioactive decay of
 333 elements in the crust, which is the weighted average of the lower and upper crust heat
 334 generation. The internal heat generation in the upper and lower crusts was estimated at
 335 $1.5 \times 10^{-6} \text{ W m}^{-3}$ and $0.72 \times 10^{-6} \text{ W m}^{-3}$, respectively (Table 2; Horton et al. 2016).
 336 λ ($\text{W m}^{-1} \text{ K}^{-1}$) is the average thermal conductivity of the crust and Z_{CPD} (m) is the CPD.
 337 The range of the CPD was estimated at 10 km to 33 km, corresponding to the average

338 Moho depth in northern Madagascar, using the centroid method of Tanaka et al. (1999)
 339 and according to the available world map of the CPD (Li et al. 2017).

340 The heat flow at 10 km (Q_{10} , mWm^{-2}) was then calculated with:

$$341 \quad Q_{10} = Q_{\text{cpd}} + A_{\text{LC}} H_{\text{LC}} + A_{\text{UC}} (H_{\text{UC}} - H_{\text{model}}) \quad (5)$$

342 where H_{LC} and H_{UC} are the thickness of the lower and upper crusts, respectively, H_{model} is
 343 the thickness of the model, and A_{LC} and A_{UC} are the heat generation of the lower and upper
 344 crusts, respectively (Table 2).

345 Adiabatic heat transfer conditions were applied to the lateral boundaries.

Table 5 Parameters for the heat transfer boundary condition

Parameters	Value			Unit
Surface temperature	$T_s = -0.0046z + 26.85$			$^{\circ}\text{C}$
Heat flow at base (Q_{10})	Min 50	Mean 99	Max 148	mWm^{-2}

346 **3.6 Parameter sensitivity**

347 The sensitivity of the model to the uncertain parameters was evaluated using the parametric
 348 sweep function implemented in COMSOL Multiphysics. The value of the parameters was
 349 set from the minimum to maximum. These parameters are basal heat flow, fault aperture
 350 and fault permeability (Tables 2 and 5). Combining these three parameters with the
 351 different fault dip scenarios (Table 1) yielded 96 simulations for the Ambilobe 2D model
 352 and 81 for Ambanja.

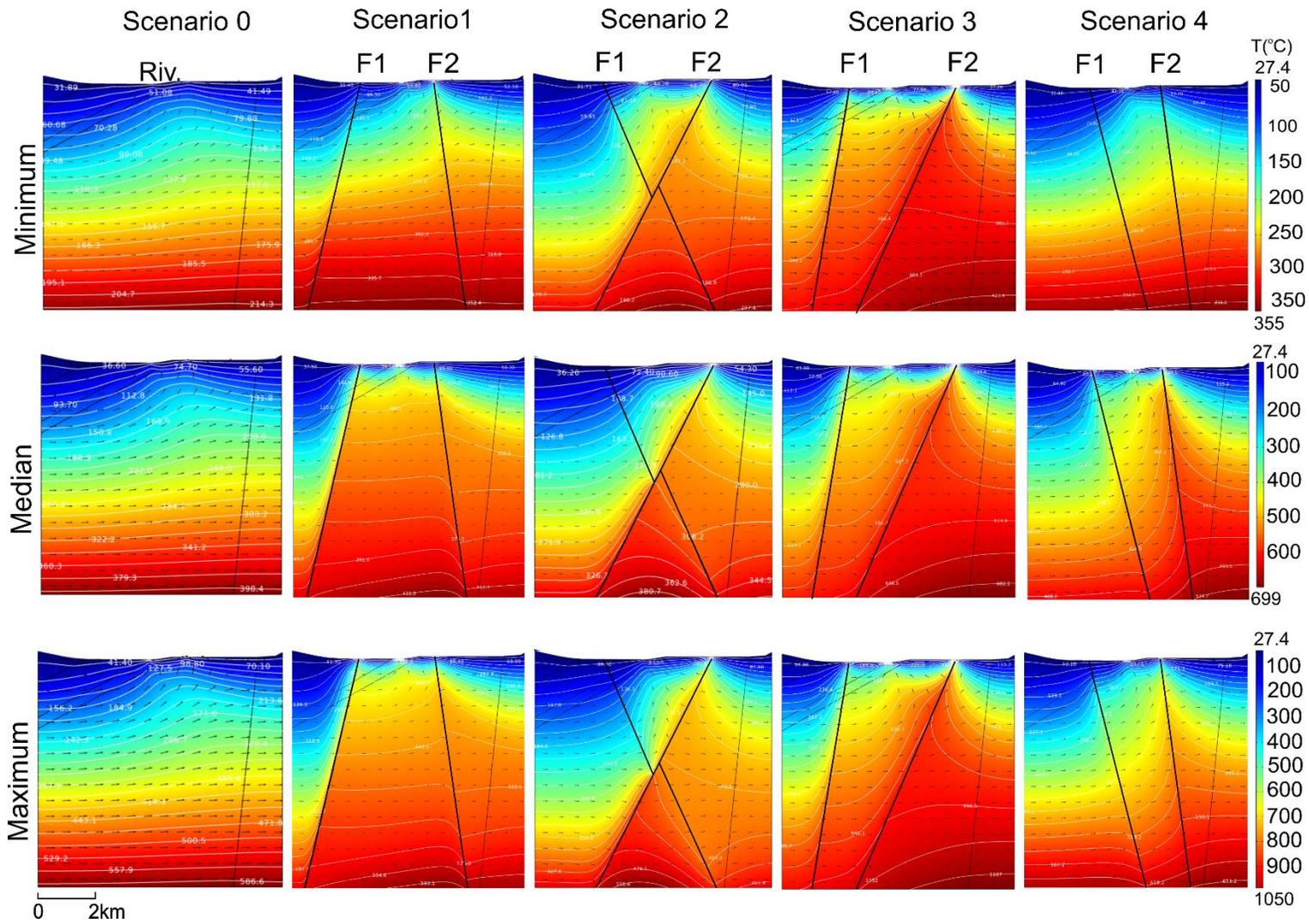
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354 **4. Results and analysis**

355 **4.1 2D subsurface temperature distribution and flow velocity**

356 The different scenarios shown in Figures 8 and 10 are for base conditions using minimum,
357 median and maximum heat flow values and average fault properties (Tables 1 and 2). The
358 simulation results confirm that the highest temperatures occur when heat flow is maximum,
359 and that fluids and heat ascend along faults compared the fault-free base case (scenario 0).
360 Temperature profiles as a function of depth along fault lines (Figures 9 and 11) show which
361 simulations best reproduce the near-surface temperature of the hot springs. The results also
362 indicate the depth at which reservoir temperature is attained, assuming the chemical
363 geothermometer provides a reliable reservoir temperature estimate. The most realistic
364 scenarios are when hot spring temperatures are attained near the upper-end of the faults,
365 and the reservoir temperature is at a reasonable depth, below approximately 2 km. The
366 most realistic simulation cases for Ambilobe are maximum heat flow value and fluids rising
367 along fault F2 in scenario 1, maximum heat flow value and fluids rising along fault F1 in
368 scenario 2, and median or maximum heat flow values and fluids rising along fault F2 in
369 scenarios 3 and 4 (Figures 8 and 9).

370

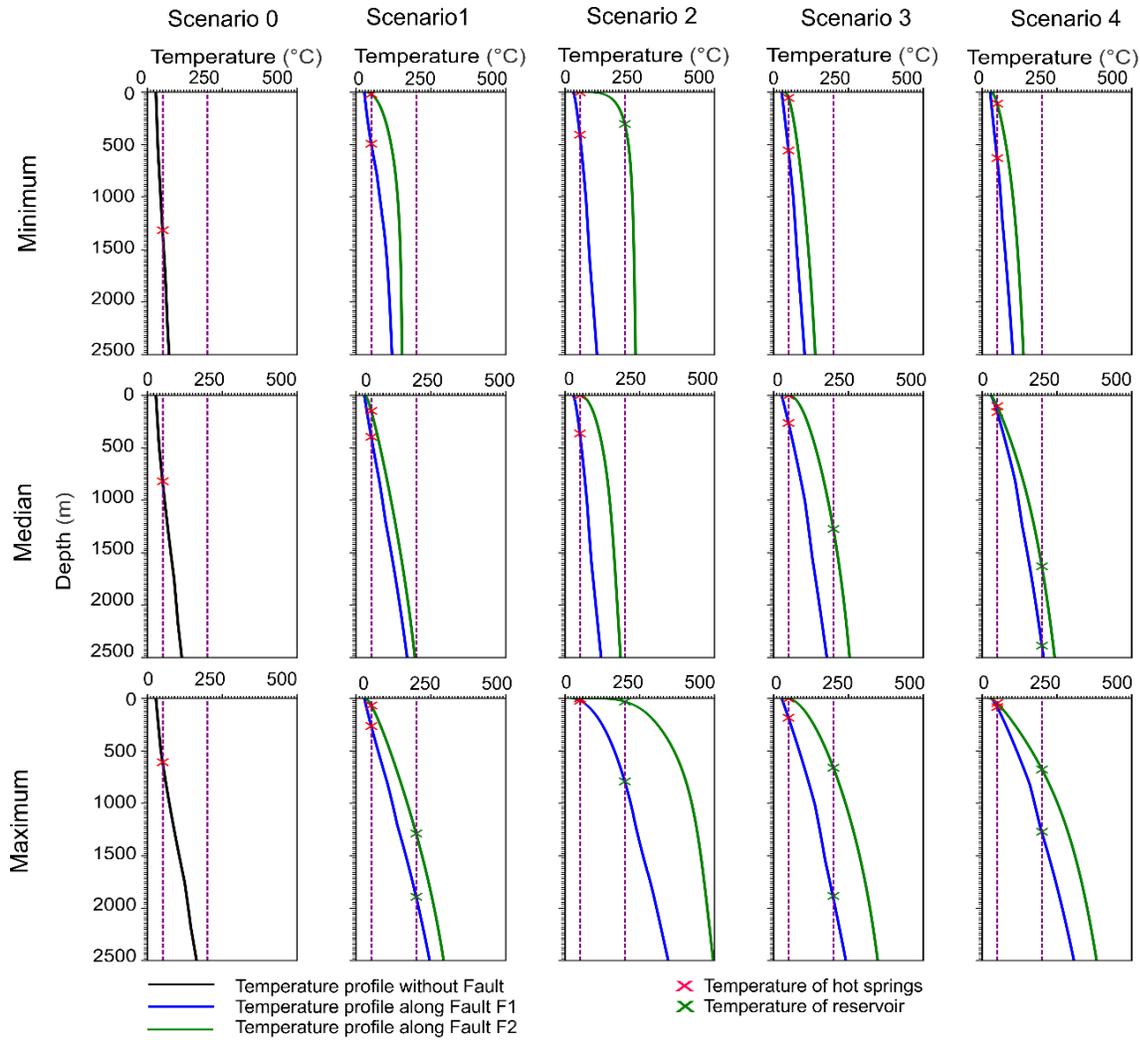


371

372 **Figure 8** Simulated temperature distribution for the Ambilobe 2D model considering different fault dips and heat flux variations

373 at 10 km depth. Black arrows indicate the velocity field and flow direction; white lines are isotherms

374 The most realistic cases for the Ambanja graben are found in scenario 1 with median and maximum
 375 heat flow values and fluids rising along fault F2 (Figures 10 and 11).



376

377 **Figure 9** Temperature profiles as a function of depth along fault lines for the Ambilobe 2D
 378 model. The temperature profiles in scenario 0 were obtained from an average cutline drawn in the
 379 fault-free model.

380

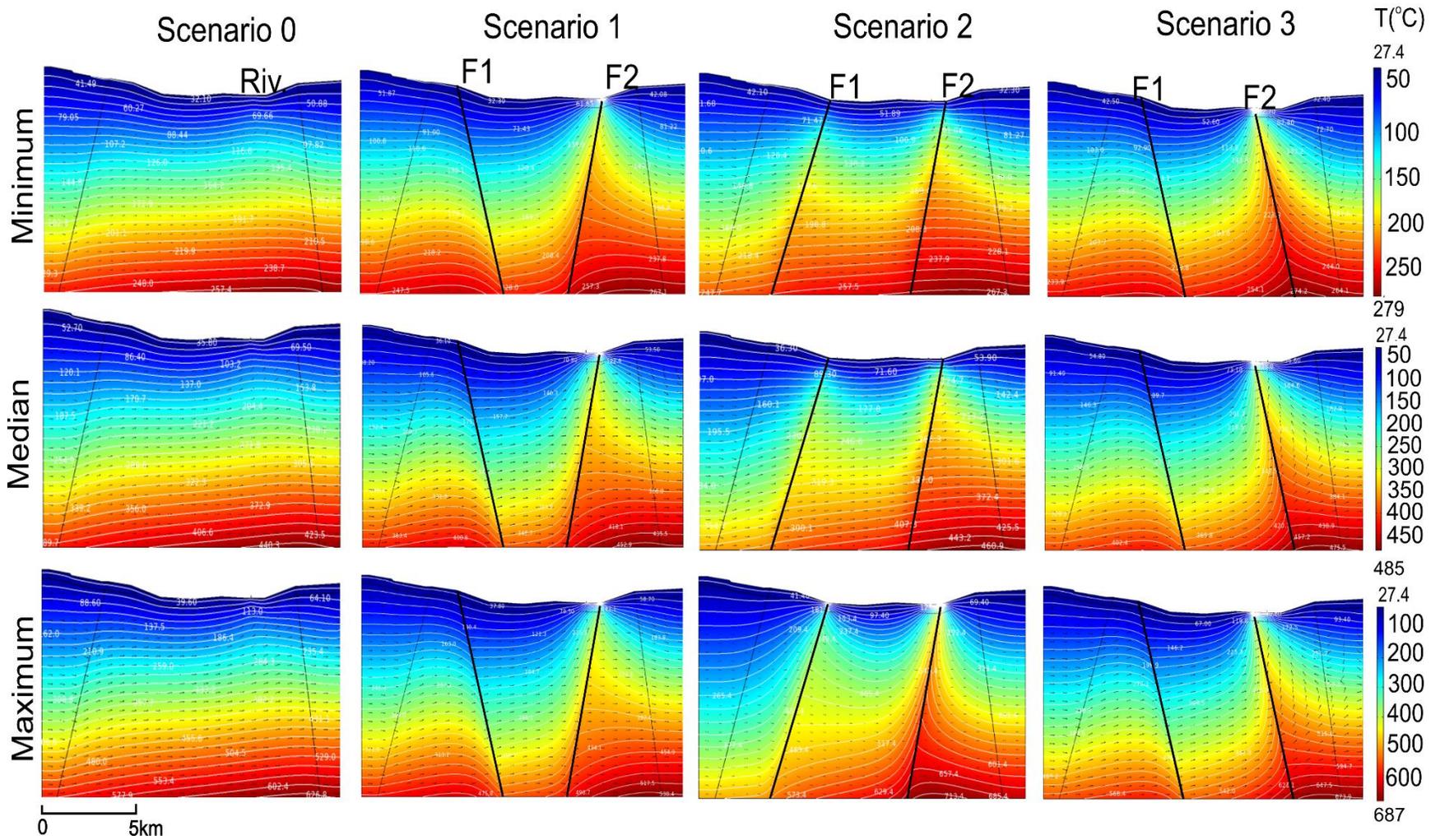
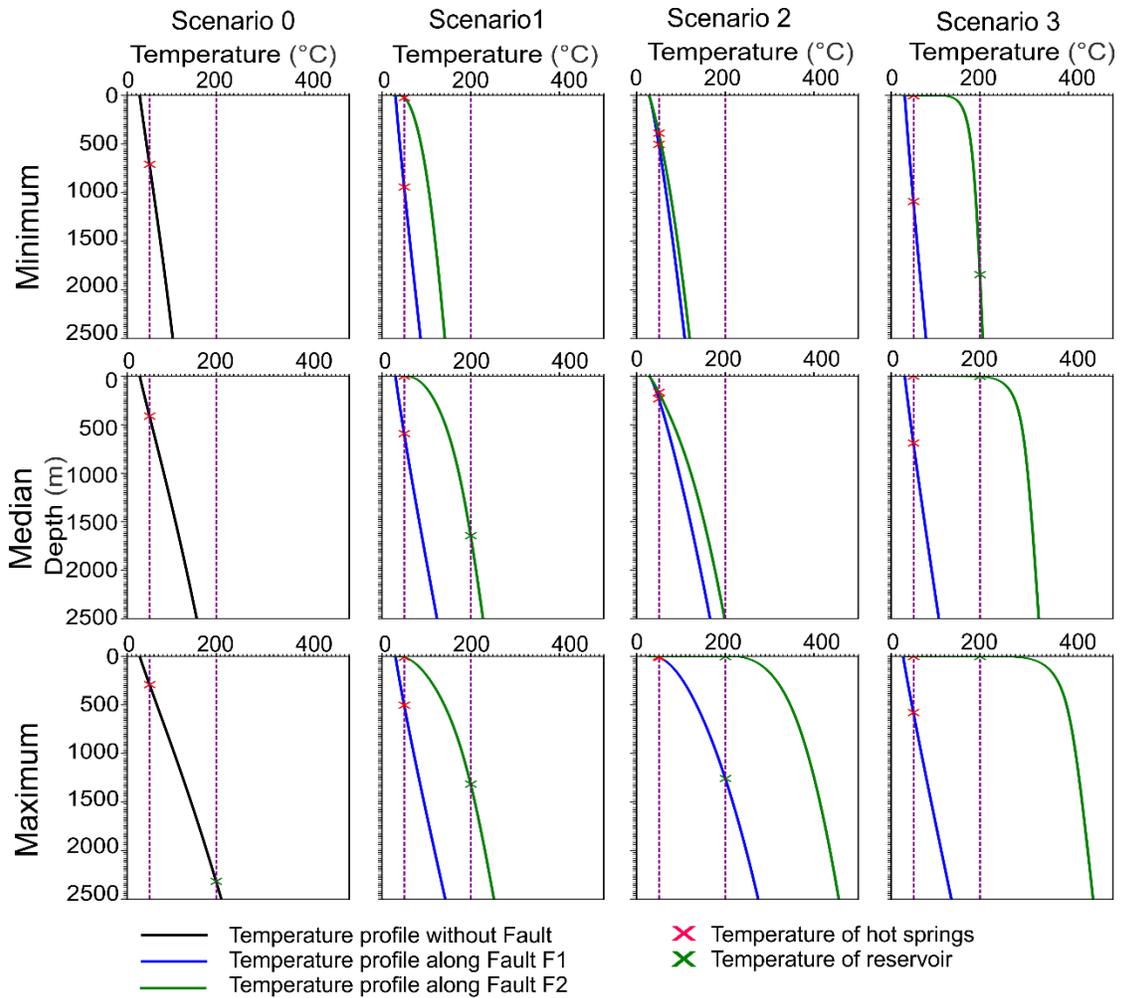


Figure 10 Simulated temperature distribution for the Ambanja 2D model considering different fault dips and heat flux variations at 10 km depth. Black arrows show the velocity field and flow direction; white lines are isotherms.



384

385 **Figure 11** Temperature profiles as a function of depth along fault lines for the Ambanja
 386 2D model. The temperature profiles in scenario 0 were obtained from an average cutline
 387 drawn in the fault-free model.

388 The magnitude of the Darcy velocity varies between 10^{-9} and 10^{-2} m s^{-1} along the faults
 389 (e.g. Figure 12). The simulated outflow velocity at the upper-ends of favorable faults
 390 (Table 6 and Figure 12) shows no difference or a 1-2 magnitude difference compared to
 391 the measured flow velocity at some hot springs, which varies between 10^{-9} and 10^{-7} m s^{-1}
 392 (Table 6; Gunnlaugsson et al. 1981).

Table 6 Simulated flow velocity at favorable faults for the most realistic scenarios for Ambilobe and Ambanja models

	Ambilobe				Ambanja	
Most realistic scenario	1	2	3 and 4	3 and 4	1	1
Heat flow Q_{10} (mWm^{-2})	Max	Max	Median	Max	Median	Max
Favorable fault	F2	F1	F2	F2	F2	F2
Fault dip	85° SE	60° NW	75° SE and 85° NW	75° SE and 85° NW	80° NE	80° NE
Measured flow at hot springs, (m s^{-1}) (Gunnlaugsson et al. 1981)	1.09×10^{-8} to 1.45×10^{-7}	9.23×10^{-9} to 1.23×10^{-8}	5.45×10^{-9} to 7.27×10^{-8}		4.26×10^{-9} to 2.89×10^{-8}	
Simulated outflow velocity at upper-ends of fault (m s^{-1})	6.47×10^{-7} to 1.21×10^{-6}	7.07×10^{-7} to 1.11×10^{-6}	9.63×10^{-7} and 1.24×10^{-6} to 2.6×10^{-7}	2.14×10^{-7} and 2.72×10^{-7} to 1.24×10^{-6}	2.32×10^{-8} to 1.19×10^{-3}	9.37×10^{-5} to 9.74×10^{-4}

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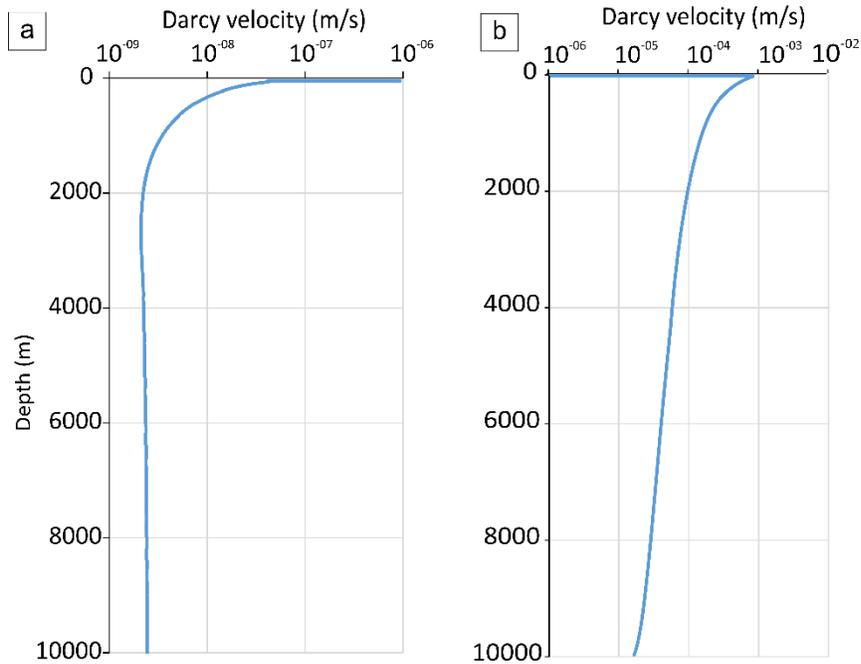
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Figure 12 a) Ambilobe 2D model, scenario 3: flow velocity along fault F2, maximum

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heat flow value. b) Ambanja 2D model, scenario 4: flow velocity along fault F2, median

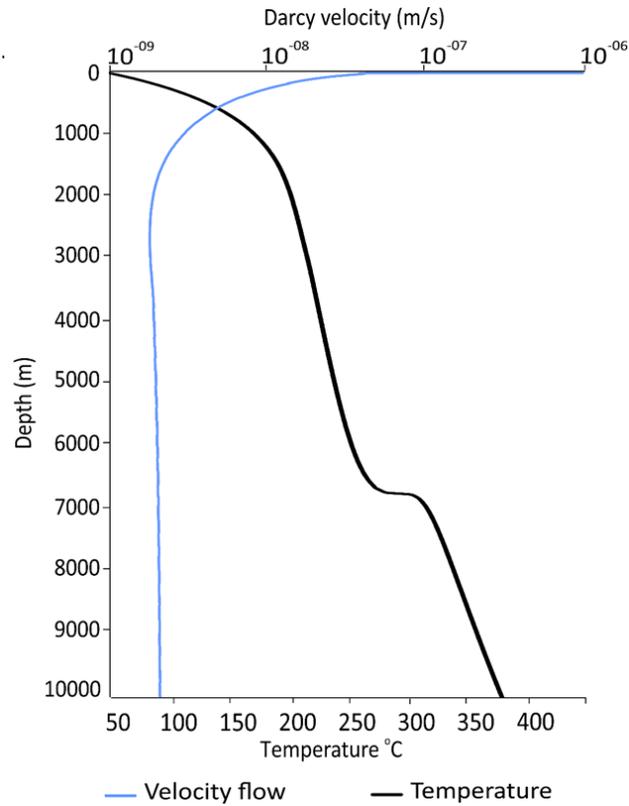
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heat flow value. Results for F1 and F2 use mean aperture and permeability values.

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Figure 13 Variation of simulated flow velocity and temperature as a function of depth along the fault. Ambilobe 2D model, scenario 3, fault F2 and median heat flow value.

417

4.2 Influence of faults

418 Faults play a fundamental role in the movement of fluids and pore pressure distribution
419 and therefore exert considerable influence over the temperature distribution. This is evident
420 when comparing scenario 0 (without faults) to faulted scenarios (Figures 8 and 10). The
421 faults serve as conduits for fluid upflow, with Darcy velocity vectors converging upward
422 along the faults toward the hot springs location. The temperature along faults can be up to
423 150 °C higher than adjacent areas (Figure 8 and 10). Heat transfer becomes conductive in
424 the surrounding host rock, where bulk permeability is lower than the high-permeability
425 zones because fluids drain towards the fault where convection occurs. Faults create

426 permeability heterogeneities in the crust, which affect fluid flow and convective heat
427 transfer, thereby influencing the location of hot springs (Faulds et al. 2010; Faulds and
428 Hinz 2015), especially at their intersections (Belgrano et al. 2016; Person et al. 2012). This
429 is consistent with the numerical modeling of deep fluid flow associated with crustal-scale
430 normal faults in the south-central Canadian Cordillera (Ferguson et al. 2009). The latter
431 reported that the permeability contrasts between host-rocks and faults acting as conduits
432 for preferential fluid flow, have the greatest influence on the subsurface temperature
433 distributions consistent with observed thermal springs. However, the presence of a fault
434 does not necessarily imply the formation of a hot spring unless the favorable conditions are
435 present that allow fluids and heat to ascend and reach the surface (e.g. López and Smith
436 1995; Thiébaud 2008)

437 Simulation scenario 3 for the Ambilobe 2D model clearly illustrates favorable conditions
438 for fluid ascension, with higher simulated temperatures near the upper-end of both faults
439 (Figure 8; Table 1) and fault dips of $< 90^\circ$ facing the fluid flow. As shown in Figure 13,
440 the fluid at the surface, reaches the highest Darcy velocity (10^{-6} m s^{-1}) which match the
441 temperature of the hot spring (50°C). A flow velocity of 10^{-8} m s^{-1} is found at the depth
442 having the reservoir temperature of 180°C .

443 On the other hand, if the fault is facing away from the fluid flow direction, like F1 in
444 scenarios 1 and 3 for the Ambanja graben model (Figure 10; Table 1), then the hydraulic
445 gradient between both ends of the fault is smaller and the simulated temperature near the
446 upper-end of the faults is lower. Similar results were reported by Moreno et al. (2018), who
447 simulated the impact of faults on the circulation of fluids originating from the basement
448 underlying the Nevado del Ruiz volcanic complex of Colombia, where hot springs are

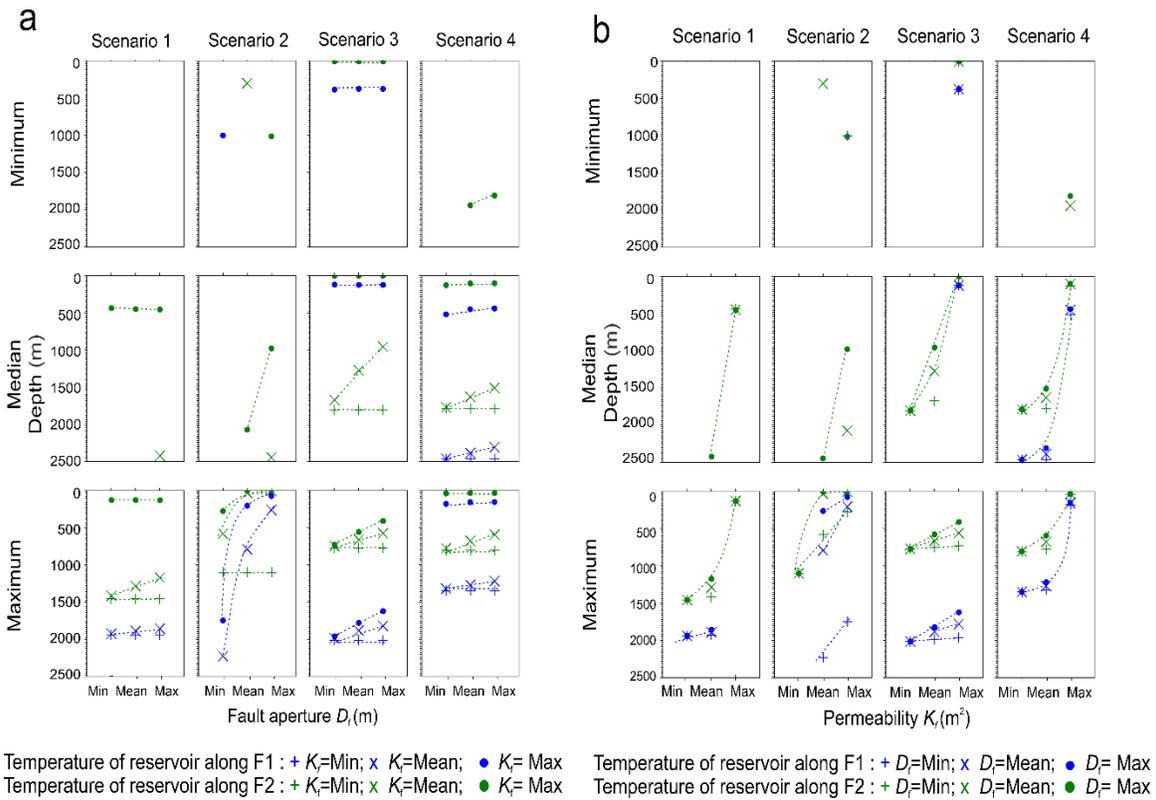
449 present. However, scenarios 1 and 2 for the Ambilobe 2D model showed that fluids are
450 able to rise to the surface along a fault with a dip facing away from the fluid flow direction
451 (F2 and F1, respectively) if it is close to a river that acts as a discharge zone (Figure 8 and
452 9). This is also seen in scenario 4. It suggests that both the fault dip and its distance from a
453 discharge zone where the hydraulic head can be low are important characteristics in favor
454 of fluid ascension.

455 Additionally, convective heat transfer along faults implies that ascending fluids are diluted
456 as they mix with groundwater of shallower origin, to the degree that half of the ascending
457 fluids will reach the upper 75 % of the fault length (Ferguson et al. 2009). This can explain
458 the finding of significant mixing of geothermal fluids with shallower groundwater
459 (Giggenbah diagram of Figure 5) and the absence of boiling hot springs in the Ambilobe
460 and Ambanja geothermal fields due to cooling along the fault between the reservoir depth
461 and the surface.

462 **4.3 Parameter sensitivity**

463 For each scenario, we investigated the variation in depth at which reservoir temperature is
464 attained as a function of basal heat flow, fault aperture and permeability (Figures 15 and

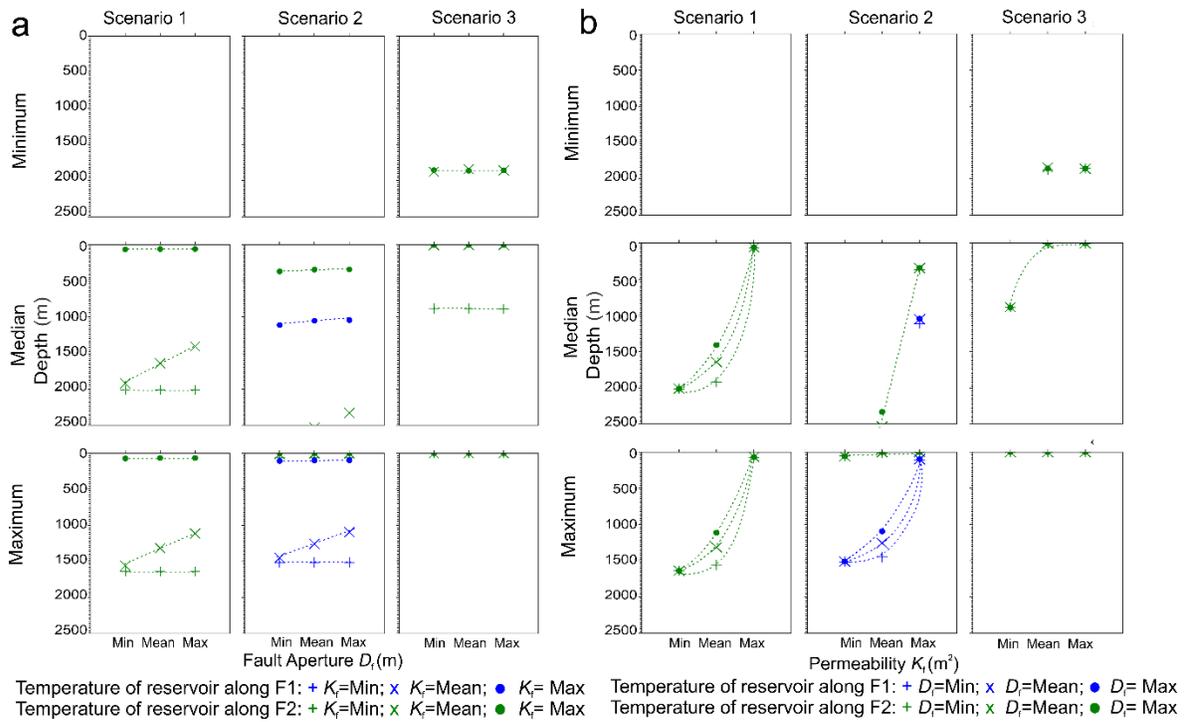
465 16).



467 **Figure 14** Depth variation of reservoir temperature along fault lines in the Ambilobe
 468 2D model according to different fault dip scenarios a) as a function of heat flow and fault
 469 aperture, and b) heat flow and fault permeability. The dotted line indicates the trend of
 470 depth variation.

471 The results reveal that the depth of reservoir temperature decreases with increasing heat
 472 flow, fault aperture and fault permeability. For example, in scenario 1 (Figure 14a), with
 473 the minimum fault aperture (D_f) value and maximum fault permeability (k_f), the depth of
 474 reservoir temperature decreases from >2500 to 200 m along fault F2 when heat flow
 475 increases from the minimum to the maximum. For the same scenario, using maximum heat
 476 flow and mean fault permeability, the depth of reservoir temperature decreases from 1400
 477 to 1100 m along fault F2 by increasing the value of fault aperture. In scenario 3 (Figure

478 14b), using minimum fault permeability and maximum fault aperture, the depth of reservoir
 479 temperature decreases from >2500 to 750 m along fault F2 as function of the heat flow
 480 value. For the same scenario, using maximum heat flow and mean fault permeability, the
 481 depth of reservoir temperature decreases from 800 to 400 m along fault F2 by increasing
 482 the fault aperture. The least favorable cases in scenarios 1 and 2 are when minimum heat
 483 flow fails to produce any points on the plots because the reservoir temperature is always
 484 deeper than 2500 m despite increases in fault aperture and permeability.



486 **Figure 15** Depth variation of reservoir temperature along fault lines in the Ambanja
 487 2D model according to different fault dip scenarios a) as a function of heat flow and fault
 488 aperture, and b) as a function of heat flow and fault permeability. The dotted line indicates
 489 the trend of depth variation.

490 The parameter sensitivity trend described for different fault dip scenarios in the Ambilobe
 491 model is the same for the Ambanja model (Figure 15). The least favorable cases correspond

492 to scenarios 1 and 2 using the minimum heat flow value because the reservoir temperature
493 is deeper than 2500 m despite increasing fault aperture and permeability.

494 We assessed the influence of basal heat flow, fault aperture and fault permeability given
495 the uncertainty associated with those inputs. Varying any of these parameters results in
496 significant differences in pressure, velocity and field temperature, enhancing or
497 diminishing fluid pathways along the fault.

498 The basal heat flow used in our models provides a first estimation of the heat flow range
499 for the geothermal region in northern Madagascar, which is comparable to the known heat
500 flows of the proposed analogue geothermal systems for Ambilobe and Ambanja discussed
501 below (Rajaobelison et al. 2020). In zones of extension and continental rifting, regional
502 heat flow estimates are high, generally from 75 to 125 mWm^{-2} (Jaupart et al. (2015)). The
503 range of heat flow for the Great Basin (USA) is from 50 to $\sim 120 \text{ mWm}^{-2}$, averaging roughly
504 90 mWm^{-2} (Blackwell D and Richards 2004). In Western Turkey, particularly in the Gediz
505 graben, the heat flow varies from ~ 50 to 140 mWm^{-2} , with values exceeding $\sim 100 \text{ mWm}^{-2}$
506 (Yilmazer et al. 2010). In the present study, the basal heat flow affects the temperature
507 distribution at depth and thus influences the geothermal gradient along permeable faults
508 (Figure 9, 8 and 10, 11). Moreover, a higher basal heat flow amplifies the convective
509 regime when the fault permeability also increases (López and Smith 1995). In turn, the
510 reservoir temperature is reached at shallower depths. However, the thermal spring
511 distribution does not appear to be a function of heat flow. Indeed, high heat flow is
512 associated with higher temperatures near the upper-ends of the fault, while hot spring
513 temperatures can be found near the upper-ends of the fault in any of the favorable fault
514 scenarios regardless of heat flow (Figures 2).

515 Fault aperture impacts heat transfer along the fault, which is amplified when fault
516 permeability is high ($k_f > 10^{-14} \text{ m}^2$), allowing for fluid ascension as shown in scenarios 1
517 and 2 for the Ambilobe 2D model of Figure 14a. Indeed, a small fault aperture
518 ($D_f > 250 \text{ }\mu\text{m}$) combined with a moderate to high fault permeability (10^{-10} - 10^{-7} m^2) allows
519 hot fluids to be found at shallow depths, $< 2 \text{ km}$ from the surface. Increasing fault
520 permeability shifts the system from petrothermal to transitional, thereby making this
521 parameter a critical factor in numerical models. By varying fault permeability in the model,
522 the transmissivity to flow along faults becomes significant when fault permeability is
523 higher than 10^{-14} m^2 , attracting hot upwelling fluids at depth (Figure 14b and 15b). An
524 optimum combination of country-rock (host rock) and fault permeabilities is also needed
525 to obtain subsurface temperature distributions consistent with observed thermal springs
526 (Forster and Smith 1989). This means, the permeability difference between the country
527 rock and the fault can increase or decrease springs temperatures (Ferguson et al. 2009;
528 Forster and Smith 1989; López and Smith 1995). In the present study, a permeability
529 difference of 4 to 7 orders of magnitude between the country rock and the fault depresses
530 the thermal field. The decrease is due to the downward flux of recharge water, while high-
531 temperature discharge associated with upward flow occurs along the fault plane. In fact,
532 the pressure that forces the water to the surface is mainly supplied by the difference in
533 elevation between the recharge and discharge areas.

534 However, it is well known that fractures and faults can seal and re-open over time through
535 multiple tectonic constraints (e.g. Ingebritsen and Manning 2010). The current seismicity
536 (magnitude $M_w > 5$ in the study areas; (Bertil and Regnault 1998) suggests that faults may
537 maintain efficient permeability over time.

538 5. Discussion

539 **5.1 Groundwater flow boundary conditions**

540 The hydraulic head applied to the lateral boundaries of the model reproduces topography-
541 driven groundwater flow from NNE to SSE in the Ambilobe model and from NW to SE in
542 the Ambanja model. Surface recharge is neglected since the goal is to evaluate the impact
543 of faults intercepting the regional flow path. At the river segment, the flow vectors are
544 directed toward the surface and the river constitutes a discharge zone (Figures 8 and 10).
545 The magnitude of ascending flow vectors increases from 10^{-10} to 10^{-2} m s⁻¹ when faults
546 intercept ascending flow vectors. The impact of the regional flow path was previously
547 highlighted by Taillefer et al. (2018), who suggested that topography (i.e., an elevated
548 water table) is the key factor controlling fluid pathways and the hot spring distribution in
549 the Têt hydrothermal system of the Eastern Pyrénées in France. Similar conclusions can be
550 made for Ambilobe and Ambanja, where the topography-driven groundwater flow affects
551 forced convective heat transfer along the faults. The flow lines within the models show that
552 the fluids originating from higher elevations reach considerable depth where they can be
553 heated and redirected towards the surface through permeable faults (Figures 8 and 10). This
554 also confirms that hydraulic heads and hydrological budgets control the regional
555 groundwater flow systems in an extensional domain geothermal play, as mentioned by
556 Moeck (2014).

557 **5.2 Model limitations**

558 As a first step, a simplified model is necessary to understand the flow and heat transfer
559 mechanisms influencing the temperature distribution in a geothermal system where crustal-

560 scale faults control the fluid migration pathway. Fault and host rock permeabilities are
561 assumed constant with depth, although they can decrease with increasing confining
562 pressure (Rajaobelison et al. 2021). With this assumption, forced convection versus
563 conduction is clearly favored. Indeed, permeability probably decreases with depth in the
564 basement due to the contrasting mechanical properties of the minerals present in the rocks,
565 such as mica and feldspar, and in faults due to sealing by the mineral precipitation (Stober
566 and Bucher 2015).

567 The scarcity of structural information in the study area is an important limitation to the
568 models. More structural field data, including dip angle and fracture density measurements,
569 would better constrain the fault dip, aperture and permeability values in the numerical
570 models. Moreover, statistical features summarized from field data are needed for the
571 stochastic processes in discrete fracture models (e.g. Ivanova et al. 2014). It is currently
572 difficult to anticipate fracture behavior at depth. Ggeophysical surveys (e.g. gravity and
573 magnetotellurics) would help to image deep structures, build more accurate 2D models,
574 and eventually develop 3D models around faults.

575 Even though these aspects limited our modeling approach, the present work successfully
576 reproduces hot spring temperatures observed at surface, with consistent reservoir
577 temperatures at reasonable depths.

578 **5.3 Geothermal exploration**

579 This study identified favorable fault characteristics that trigger fluid ascension and favor
580 the formation of geothermal energy sources, knowledge that can assist geothermal
581 exploration efforts to better identify exploration targets. More specifically, the target

582 should be normal faults with $< 90^\circ$ dips facing the regional fluid flow path driven by
583 topography. Fault permeability must be higher than the host rock, corresponding to the
584 critical range of permeability under which forced convection occurs, combined with a
585 minimum aperture of 250 μm .

586 The simulation results also revealed that an average drilling depth of 1 to 2 km along
587 favorable faults should reach the temperature interval of 150–200 $^\circ\text{C}$ (Figures 8 and 10).
588 This finding can positively impact an exploration project since drilling cost increases
589 nonlinearly with depth (e.g. Augustine et al. 2006).

590 **6. Conclusions**

591 This study presents, for the first time, 2D numerical models simulating groundwater flow
592 and heat transfer according to a realistic topography and fault hypothesis in Madagascar.
593 The aim is to better understand heat transfer mechanisms involved with the geothermal
594 systems of the Ambilobe normal fault zone and Ambanja graben in northern Madagascar.
595 Numerical simulations are used to define the large-scale temperature field in such
596 extensional-type geothermal systems. The resulting simulated temperature distribution
597 appears to be characteristic of conductive heat transfer in a low-permeability rock matrix
598 and forced convective heat transfer along faults, representing favorable conditions that
599 facilitate fluid ascension. The most realistic scenarios are when the hot spring temperature
600 is attained near the upper-end of the fault and the reservoir temperature is at a reasonable
601 depth, shallower than ~ 2 km. The simulated flow velocity at the upper-ends of faults is
602 comparable to those measured in surface hot springs.

603 Our findings support previous interpretations of conceptual models in northern
604 Madagascar, where conduction is the dominant heat transfer mechanism in low-
605 permeability rock matrix, except along faults that experience a strong hydraulic gradient
606 and provide a path for fluids to rise with forced convective heat transfer as the dominant
607 mechanism

608 Numerical models used in this study can be a predictive tool to help define geothermal
609 exploration strategies in similar normal fault zone and graben settings. Further
610 hydrogeological assessment using stable isotope analyses on springs and groundwaters can
611 help improve and support the simulated fluid circulation concept by defining infiltration
612 altitudes and determining fluid origin. Deep borehole data, such as temperature logs, will
613 also be required for the next steps to realistically constrain the temperature prediction and
614 advance geothermal exploration in North Madagascar.

615 **Author contributions**

616 MR: Data collection, investigation, conceptualization, methodology, Writing (original
617 draft preparation), formal analysis. JR and MM: Supervision, resources, project leads. JR,
618 CD and MR: Validation. JR, MM, CD and SL: Drafting and editing. All authors reviewed
619 the manuscript and have read and agreed to the published version of the manuscript.

620 **Competing interests**

621 The authors declare that they have no competing interests.

622 **Availability of data and materials**

623 The relevant datasets analyzed in this study are all presented in the manuscript.

624 **Acknowledgments**

625 The authors would like to thank the Canadian Francophonie Scholarship Program CFSP,
626 which supported the first author with a scholarship. The UNESCO International geoscience
627 program (IGCP) is also acknowledged for providing a framework that supported
628 collaboration among the members of the IGCP-636 group involved in geothermal research
629 and who participated as coauthors to this paper. Additional thanks go to Elie R. for
630 discussions and invaluable help with modeling issues using COMSOL.

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1 **Understanding heat transfer along extensional faults: the case of the Ambilobe and**
2 **Ambanja geothermal systems of Madagascar**

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4 **M. Rajaobelison**

5 INRS – Institut national de la recherche scientifique

6 490, rue de la Couronne. Québec (Québec) G1K 9A9 Canada

7 Miora.Mirah.Rajaobelison@inrs.ca

8 ORCID : 0000- 0002- 8125-5210

9 Corresponding author

10 **J. Raymond**

11 INRS – Institut national de la recherche scientifique

12 490, rue de la Couronne. Québec (Québec) G1K 9A9 Canada

13 ORCID: 0000-0001-7596-2800

14 **M. Malo**

15 INRS – Institut national de la recherche scientifique

16 490, rue de la Couronne. Québec (Québec) G1K 9A9 Canada

17 ORCID: 0000-0001-5941-9736

18 **C. Dezayes**

19 BRGM – Bureau de recherches géologiques et minières, 3 Avenue Claude Guillemin,

20 45100 Orléans, France

21 ORCID: 0000-0001-7813-359X

22 **S. Larmagnat**

23 Geological Survey of Canada, 490, rue de la Couronne, Québec, QC G1K 9A9, Canada

24 ORCID:

25 **Keywords:** Energy; Geothermal; Heat transfer; Faults, Numerical modeling, Madagascar

26 **Abstract**

27 Understanding the role of faults where forced convective heat transfer is the dominant
28 mechanism giving rise to hot springs is critical in geothermal exploration in extensional
29 environments. This study uses two-dimensional models of coupled fluid flow and heat
30 transfer along cross-sections perpendicular to faults and the regional topography to identify
31 favorable fault conditions for geothermal system development in northern Madagascar.
32 Structural data collected at surface were used to define fault scenarios and simulate the
33 ascension of hot fluids to reproduce hot spring temperatures in the Ambilobe normal fault
34 zone area and the Ambanja graben structure. Fault dips facing topography- driven
35 groundwater flow was shown to be favorable, and hot spring temperatures could be
36 reproduced when the fault permeability was $>10^{-14}$ m². Faults located in a discharge zone
37 near a river were the most favorable for fluid ascension, regardless of their dip.
38 Constraining the model with a basal heat flow between 90 and 148 mWm⁻² at a depth of
39 10 km allowed the reservoir temperature to reach 150–200 °C at depths of 2 km or
40 shallower along favorable faults.

41 **1. Introduction**

42 Economic activity in the northern region of Madagascar relies on export products such as
43 vanilla, cocoa and coffee that are grown and transformed locally. Madagascar is one of the
44 largest vanilla exporters in the world (UNComtrade, 2018). The energy used to transform
45 these products relies heavily on fossil fuels and wood. Off-grid communities, mainly in

46 remote areas, use traditional biomass such as firewood and charcoal as their main source
47 of energy, inducing deforestation and water resource degradation, along with biodiversity
48 and soil loss, as has already happened in many Madagascar communities. Renewable
49 sources, such as geothermal energy, are expected to play a more prominent role in future
50 energy production.

51 Ambilobe and Ambanja, two areas in northern Madagascar, have been characterized for
52 their geothermal potential and respectively classified as a graben border-fault liquid-
53 dominated moderate-temperature system and a fossil magmatic liquid-dominated
54 moderate-temperature system (Rajaobelison et al. 2020). In this classification scheme
55 based on the extensional type, the fault and lithologic-diagenetic characteristics affecting
56 porosity are thought to control formation permeability. As reported by Rajaobelison et al.
57 (2020), the average matrix permeability of fracture-free rocks in these two areas was
58 evaluated between 10^{-13} and 10^{-18} m², which is low, while the average porosity is ~5.7 %,
59 which is low or poor (5–10 %) according to Levorsen and Berry (1967); Tiab and
60 Donaldson (2016). However, this matrix permeability has to be considered the lower bound
61 of formation permeability as fractures are common in such an extensional tectonic setting.
62 The occurrence of thermal springs along a major fault zone in Ambilobe and a graben
63 structure in Ambanja confirms that advective heat transfer can take place within fractured
64 rocks (Rajaobelison et al. 2020). The equilibrium formation temperature at depth,
65 estimated using chemical geothermometers (Gunnlaugsson et al. 1981), ranges from 140
66 to 200 °C, high enough to be used for scalding vanilla beans (~60 °C), heating greenhouses
67 (> 40 °C; Lindal 1973), and generating electricity (> 80 °C; Grasby et al. 2011; Tomarov
68 and Shipkov 2017). Fluids from geothermal sources with temperatures below 120 °C can

69 be used to generate electricity using an optimized Organic Rankine Cycle (e.g. Chagnon-
70 Lessard et al. 2020; Liu et al. 2017; Shi and Pan 2019).

71 No exploration boreholes have been drilled in northern Madagascar, so the optimal depth
72 for finding geothermal sources remains unknown, as do the geothermal gradient and heat
73 flux density. Previous work classified geothermal play types and evaluated rock thermo-
74 hydraulic properties from surface outcrops to better understand heat transfer mechanisms
75 at depth (Rajaobelison et al. 2020; Rajaobelison et al. 2021). Crustal-scale faults have been
76 identified as potential targets for geothermal exploration, but further work is needed to
77 better understand their role in the subsurface heat transfer mechanisms that control the
78 depth and extent of geothermal sources. Fault influence must be taken into account when
79 exploring geothermal energy sources, especially the influence of the large-scale faults
80 identified by surface mapping and shown on the geological maps of Madagascar by Roig
81 et al. (2012) and Tucker et al. (2014). Therefore, numerical modeling was used to simulate
82 groundwater flow and heat transfer according to various fault scenarios affecting the
83 geothermal energy sources associated with petrothermal systems in this extensional
84 domain of Madagascar.

85 Numerical modeling has been previously used to simulate the depth distribution of
86 temperature to better understand fractured geothermal reservoirs (e.g. Bakhsh et al. 2016;
87 Corbel et al. 2012; Hao et al. 2012; Holzbrecher et al. 2010). Faults that serve as conduits
88 and increase permeability (e.g. Brogi et al. 2021; Ferrill et al. 2004; Liotta et al. 2021;
89 Zucchi 2020) are important targets for geothermal resource exploration, but if they act as
90 barriers and decrease permeability (e.g. Gibson 1998), they can compartmentalize the
91 reservoirs, making it challenging to access and exploit the resource (Loveless et al. 2014).

92 Furthermore, the prediction and modeling of coupled fluid flow and heat transfer processes
93 in naturally fractured rock systems are critical components in energy recovery analysis
94 (Hao et al. 2012). In addition, numerical modeling of hydrothermal systems has often been
95 used to explain hot spring occurrences and explore their controlling factors (e.g. Bense et
96 al. 2008; Forster and Smith 1989; Guillou-Frottier et al. 2013; López and Smith 1995;
97 Magri et al. 2016; Taillefer et al. 2018; Volpi et al. 2017). Recently, Szijártó et al. (2019);
98 and Szijártó et al. (2021) used numerical modeling to investigate the conditions that can
99 induce and favor forced convection. Moreno et al. (2018) demonstrated that the orientation
100 of the fault dip in relation to the direction of regional groundwater flow driven by
101 topography could affect groundwater uprise and, consequently, hot spring occurrence and
102 temperature.

103 This study aims to understand the role of faults on forced convective heat transfer that gave
104 rise to hot springs in northern Madagascar, thereby providing fundamental knowledge that
105 can be used to improve geothermal exploration concepts. Our working hypothesis is that
106 fault dip at depth, which is currently unknown, can affect the rise of hot fluids. We
107 developed numerical groundwater flow and heat transfer models to reproduce the near-
108 surface temperatures of hot springs since this is the only information available in the area
109 to validate simulations. We present innovative concepts supported by 2D numerical
110 simulations of deep subsurface temperature in northern Madagascar that test seven base-
111 case fault scenarios or hypotheses. We identified fault characteristics that favored the
112 formation of geothermal energy sources to help advance geothermal exploration.

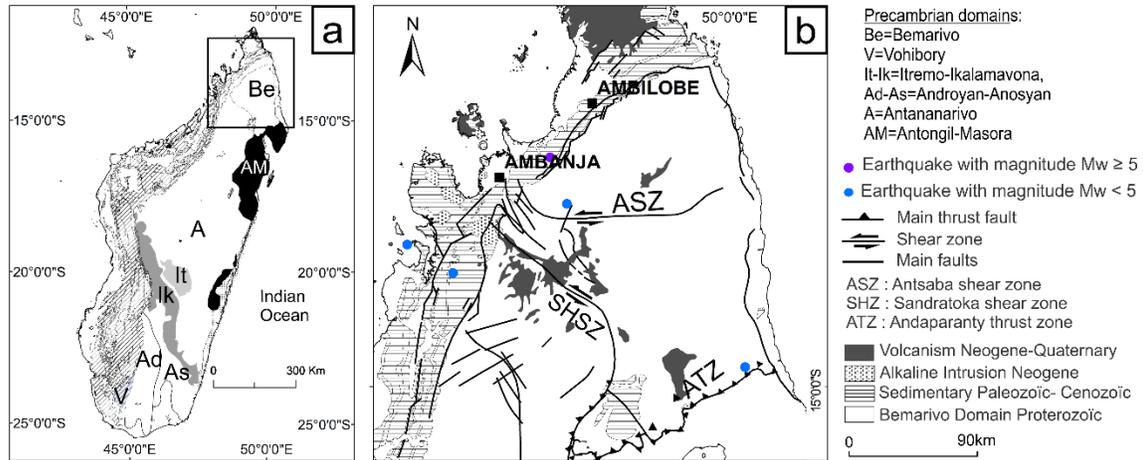
113 2. Geological setting and geothermal context

114 2.1 Tectonic framework and regional fault system

115 The Bemarivo domain, one of the six geodynamic domains forming the Madagascar
116 Shield, underlies the northern end of Madagascar, where the geothermal areas of interest,
117 Ambilobe and Ambanja, are situated. This Neoproterozoic domain is composed of
118 Cryogenian igneous rocks, with a cryptic Paleoproterozoic basement accreted to the
119 Greater Dharwar Craton in latest Ediacaran to earliest Cambrian time, 0.53–0.51 Ga
120 (Tucker et al. 2014). The Bemarivo domain has been interpreted as an assemblage of two
121 juvenile arc terranes (Figure 1) with estimated ages between c. 750 and 720 Ma (Thomas
122 et al. 2009). The east-west Antsaba shear zone, a major ductile structure, separates these
123 northern and southern terranes. The shear zone, about 15 km across at its widest location
124 in the west (Thomas et al. 2009), is interpreted as a subduction zone along which the
125 northern and southern terranes were amalgamated (Armistead et al. 2019). Contrary to the
126 suggestion of Thomas et al. (2009) and Armistead et al. (2019), the Bemarivo domain is
127 considered a single domain based on the lithostratigraphy and ages reported in Tucker et
128 al. (2014).

129 Mesozoic and younger movements along the Antsaba shear zone produced a variety of
130 faults and dykes related to the break-up of Gondwana and rifting in the Mozambique
131 Channel. The extensional phases from Triassic to Jurassic (Karoo rift) gave rise to NNE-
132 SSW and NNW-SSE faults, whereas faults generally striking N140°-N160° were
133 transformed into wrench faults with dextral movement during Jurassic-upper Cretaceous
134 times, coherent with the development of the Davie Ridge (Lardeaux et al. 1999). Numerous
135 NE-SW and NW-SE faults are consistent with the identified faults and the regional Plio-

136 Quaternary direction of extension (N65°E to N85°E) observed in the volcanic region of
137 Montagne d’Ambre, in the extreme north of Madagascar (Chorowicz et al. 1997)



139 **Figure 1** Simplified geological maps showing a) the six main geodynamic
140 Precambrian domains that form the Madagascar Shield (modified from De Waele et al.
141 2011; Tucker et al. 2014), b) and a close-up of the tectonic framework of the Bemarivo
142 domain in northern Madagascar (modified from Armistead et al. 2019; Thomas et al. 2009),
143 enclosing the Ambilobe and Ambanja study areas.

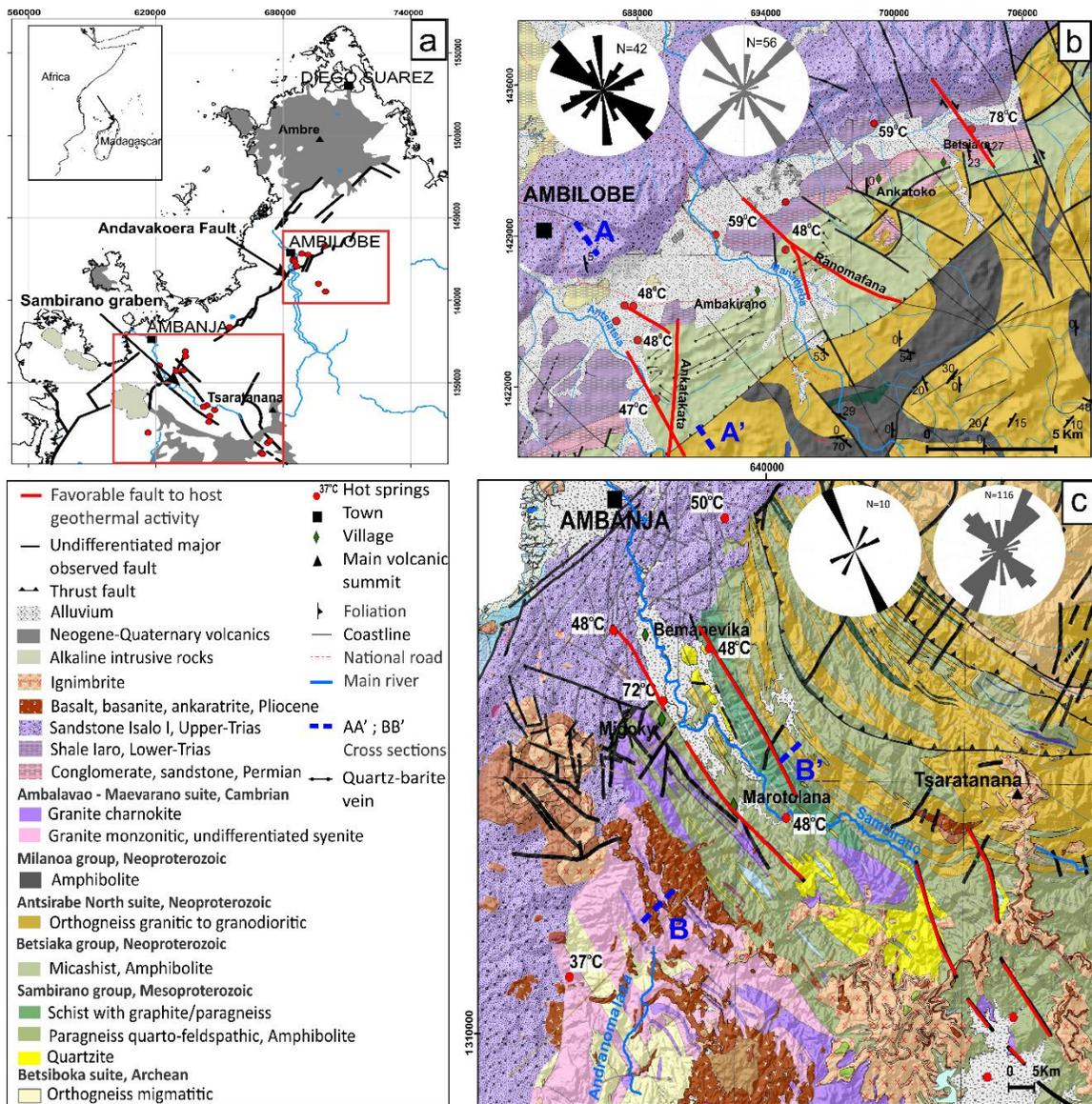
144 The Ambilobe area is located in the Andavakoera fault zone, a major NE-SW normal fault
145 delineating the contact between sedimentary sequences and basement rocks of the northern
146 Bemarivo domain. Numerous undifferentiated NW-SE faults and NW-SE strike-slip faults
147 with dextral or sinistral movements can be seen on the geological map (Figure 2b) and in
148 the field (Figure 3a). The strike-slip faults include the faults near the Betsiaka hot springs
149 and undifferentiated normal faults of Ranomafana and Ankatakata (Figure 2b). The main
150 fault and fracture systems are dominated by NNW-SSE, NE-SW and N-S orientations.

151 Fracture orientations from field measurements and fault orientations from geological map
152 are shown on the rose diagram of Figure 2b.

153 The Ambanja area is located in the graben structure in the Proterozoic basement units of
154 the southern terrane of the Bemarivo domain. The graben is oriented NW-SE, and its
155 average width is 4 km. The main faults and fractures dominantly strike NNW-SSE. The
156 rose diagrams of fracture orientations from field measurements as well as the faults
157 orientations from the geological map are shown on Figure 2c. Some metric fractures were
158 observed at the outcrop scale (Figure 3b)

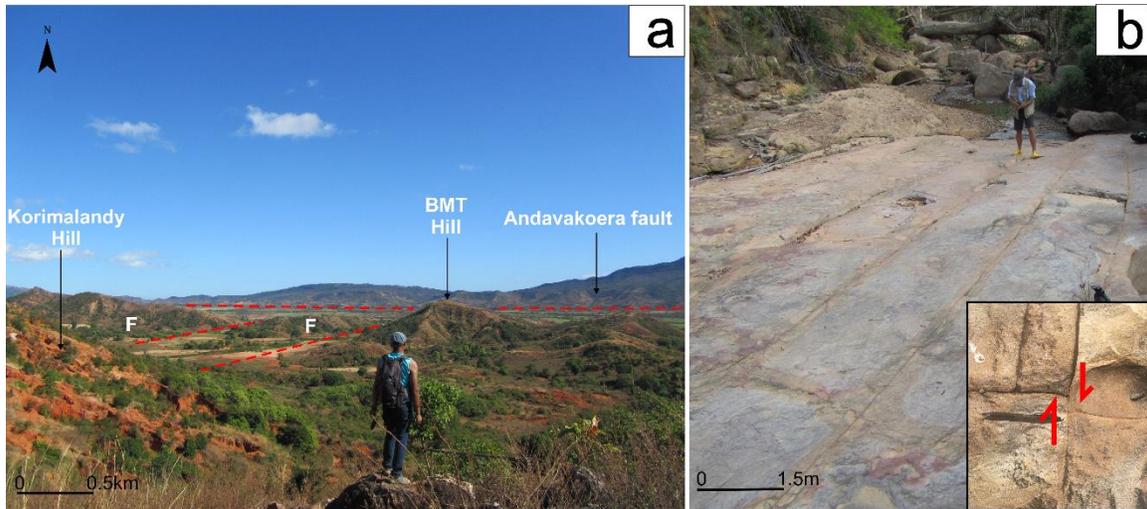
159 **2.2 Favorable structural patterns**

160 In a comprehensive inventory of the structural settings of geothermal systems in the Great
161 Basin region of western USA, Faulds and Hinz (2015) identified the most favorable
162 dominant faulting patterns to host geothermal activity in the extensional to transtensional
163 terranes, and more specifically in areas where the bulk of the geothermal resources are
164 likely hidden. Applying the same principles to the Ambilobe and Ambanja areas, the
165 identified favorable fault structures are: 1) major normal fault segments, i.e., near the
166 displacement maxima of the NE-SW Andavakoera fault and the NW-SE fault-borders of
167 the Ambanja graben structure intersections between two normal faults (Figure 2b and 2c),
168 and 2) or between normal faults and transverse oblique-slip faults (Figure 2c).



169

170 **Figure 2** (a) Location of the Ambilobe and Ambanja geothermal areas. (b) and (c)
 171 Detailed geology of each area (modified from Roig et al. 2012). The rose diagrams
 172 illustrate the major fracture trends (in black) established from field data collected in 2018
 173 and the major faults trends (in grey) established from the map data of Roig et al. (2012).



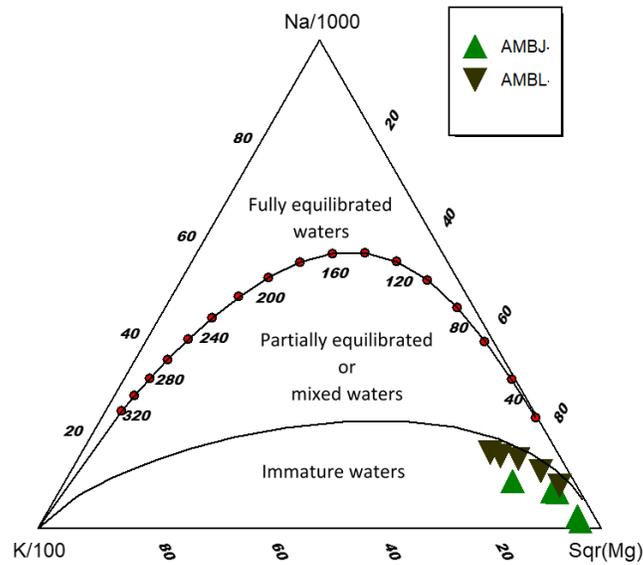
174

175 **Figure 3:** a) Field view of the Andavakoera fault line and its conjugated faults (F). b)
176 Metric fractures in the Ambanja sandstone formation with close-up illustrating fracture
177 movements.

178 At the surface, hot springs reach a temperature varying from 50 to 72 °C in both areas
179 (Besairie 1959; Gunnlaugsson et al. 1981). Waters from the hot springs have high Mg
180 concentrations and fall into the immature field on the ternary Na-K-Mg diagram of
181 Giggenbach (1988), indicating dilution of the geothermal fluid along its path to the surface
182 (Figure 4). The geothermal fluid thus mixed with meteoric and shallow groundwater.

183 Using chemical geothermometers (Gunnlaugsson et al. 1981) and the Giggenbah diagram
184 (Figure 4), the reservoir temperatures in the Ambilobe and Ambanja areas are expected to
185 be 140 and 200 °C, respectively.

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193 **Figure 4:** Chemical composition of waters from the Ambilobe (AMBL) and Ambanja
194 (AMBJ) hot springs plotted on a ternary Na-K-Mg diagram (Giggenbach 1988). The Na,
195 K, Mg concentrations were reported in Gunnlaugsson et al. (1981).

196

2.3 Lithosphere structure and geological formations

197 In the Bemarivo domain, the Moho is at a depth of 33 km (Andriampenomanana et al.
198 2017). The thickness of the upper crust is up to 20.5 km, and its composition is assumed to
199 be primarily paragneiss and sedimentary rocks which have an average thickness of 4 km.
200 The lower crust is assumed to be composed of mafic rocks with an average thickness of
201 12.5 km.

202 The geological formations of the Ambilobe and Ambanja areas and their thermo-hydraulic
203 properties have been described in Rajaobelison et al. (2020); and Rajaobelison et al. (2021).
204 The Permo-Triassic sedimentary rocks of the Ambilobe Basin, overlying the Proterozoic
205 basement of the Bemarivo domain, are the main formations in the Ambilobe area. The

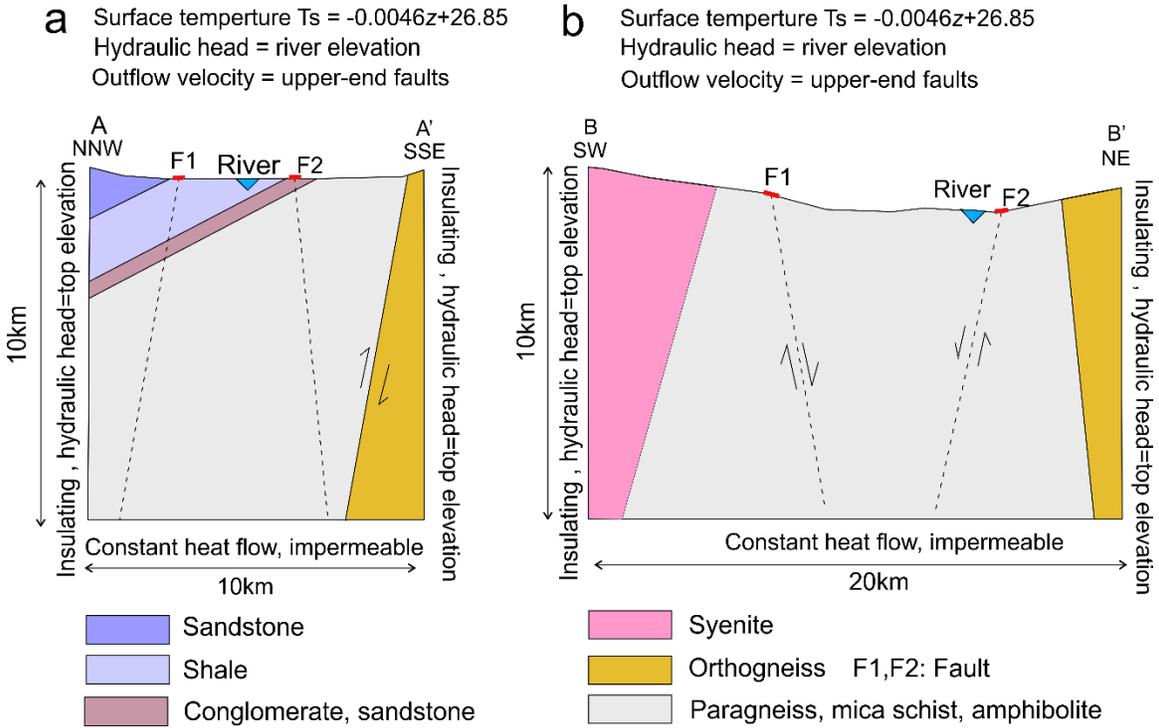
206 Proterozoic basement rocks of the Bemarivo domain are the only geological formations
207 exposed in the Ambanja area (Figure 2).

208 **3. Development numerical heat transfer model**

209 **3.1 Conceptual model and assumptions**

210 The geometry of the models (Figure 5) accounts for the topography on NNW-SSE (AA')
211 and NE-SW (BB') cross-sections (Figures 2b and 2c) that pass through, respectively, the
212 Andavakoera normal fault zone at the contact between sedimentary sequences and
213 basement rocks in the Ambilobe area, and the graben structure in the Ambanja area. The
214 dominant sedimentary and basement units have been considered in the models. The cross-
215 sections are perpendicular to the main undifferentiated faults observed near hot spring
216 occurrences. The faults represented in the models are N010° Ankatakata post-Triassic
217 normal oblique-slip faults in the Ambilobe area and N140° border faults in the Ambanja
218 graben (Figures 2b and 2c). These faults appear on the geological map of Madagascar
219 produced by Roig et al. (2012).

220 Different modeling scenarios were defined to investigate the influence of fault dip on
221 groundwater flow and heat transfer processes (Table 1). The dips in the two models range
222 from 60° to 85° since dips from 60° to vertical have been shown to cause variations in the
223 pressure and temperature of subsurface fluids (Cherubini et al. 2013). These modeling
224 scenarios were based on the geological maps of Ambanja and Ambilobe, although many
225 uncertainties remain about fault dip and down-dip continuity at depth, which justifies the
226 use of various scenarios. The models simulate the potential temperature distribution for the
227 Ambilobe and Ambanja geothermal areas according to fault dip influence.



229

230 **Figure 5:** Geometry and boundary conditions of the 2D numerical model based on the
 231 geological cross-sections (AA') and (BB') in Figure 2, representing a) the Andavakoera
 232 normal fault zone at the basement-sediment contact in the Ambilobe area, and b) the
 233 Ambanja graben.

234

Area	Faults	Dip	Scenario
Ambilobe	F1; F2	No fault	0
		70° NW; 85° SE	1
		60° NW; 60° SE	2
		80° SE; 75° SE	3
		80° NW; 85° NW	4
Ambanja	F1; F2	No fault	0
		80° SW; 80° NE	1
		75° NE; 80° NE	2
		75° NW; 80° NW	3

235

3.2 Governing equations

236 The models were developed using the subsurface flow module with a finite element method
 237 in the COMSOL Multiphysics software. The module couples groundwater flow simulated
 238 with Darcy's law and heat transfer in porous media. This made it possible to simulate
 239 forced convective heat transfer, which occurs along major faults where the host rock is
 240 considered an equivalent porous medium. Steady-state flow and heat transfer were
 241 numerically resolved according to the partial differential equation 1 and the input
 242 parameters summarized in Table 2. Sedimentary rocks and granitic and paragneiss
 243 basement rocks were considered low-permeability 2D units using the equivalent porous
 244 medium, where fluids can circulate. Faults are discrete 1D linear elements superposed on
 245 the 2D porous medium, where flow and heat transfer are solved simultaneously. Coupling
 246 between heat transfer and fluid motion occurs through the velocity field.

$$247 \quad \lambda_b \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right) - \rho_f c_f \left(u_x \frac{\partial T}{\partial x} + u_z \frac{\partial T}{\partial z} \right) + A = 0 \quad (1)$$

248 where λ_b ($\text{Wm}^{-1}\text{K}^{-1}$) is the bulk thermal conductivity; T ($^{\circ}\text{C}$) is absolute
 249 temperature; u (m s^{-1}) is the velocity vector determined from simulations of fluid flow
 250 quantified with Darcy's law, ρ_f (kg m^{-3}) is the density of the fluid, c_f ($\text{J kg}^{-1} \text{K}^{-1}$) is the heat
 251 capacity of the fluid, and A (10^{-6}W m^{-3}) is the radiogenic heat production.

252

3.3 Geometry and subsurface properties

253

3.3.1. Geometry

254

- Ambilobe

255

The model has a width of 10 km and a depth of 10 km (Figure 5a). The sedimentary units

256

dip 20-30° to the NE. Table 2 details the material properties of the 5 lithological domains.

257

The reverse fault F marks the contact between the mica schist and orthogneiss formations,

258

and F1 and F2 are the mains faults represented in the models.

259

- Ambanja

260

The model has a rectangular geometry 20 km wide and 10 km deep (Figure 5b). Table 2

261

details the material properties of the 3 lithological domains. The properties of the border

262

faults of the graben, represented by F1 and F2, are also included in the table.

263

3.3.2. Thermohydraulic properties and internal heat

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generation

265

The thermohydraulic properties of the model units were based on average properties

266

measured in the laboratory for each geological formation reported by Rajaobelison et al.

267

(2021), as summarized in Table 2. They are assumed to be constant with depth. Porosity \emptyset

268

and permeability k (m^2) were evaluated with transient measurements using the combined

269

AP-608 gas permeameter–porosimeter from Core Test Systems with nitrogen as the gas

270

source. The average bulk density ρ ($kg\ m^{-3}$) was obtained from porosity assessments.

Table 2 Model input parameters

Parameter	Value						Unit	Reference
Area	Ambilobe							
Formation	Sediments			Basement		Ambanja Basement		
Geological Units	Permian Sandstone	Eo Triassic shale	Triassic sandstone	Mica Shist Amphibolite	Ortho-gneiss	Syenite	Para-gneiss	
Mean ϕ	0.07	0.08	0.07	0.11	0.05	0.001	0.02	Fractional
Mean k	1.4×10^{-13}	1.0×10^{-17}	1.0×10^{-16}	1.0×10^{-15}	1.0×10^{-16}	1.0×10^{-18}	1.0×10^{-15}	m ²
Mean λ	3.6	2.5	3.5	2.6	3.4	2.6	2.7	W m ⁻¹ .K ⁻¹
Mean ρ	2542	2382	2628	2735	2678	2700	2678	kg.m ⁻³
Mean c	904	875	919	879	846	875	830	J kg ⁻¹ K ⁻¹
Mean A	1.14	0.72	1.25	0.58	0.38	1.35	0.38	10^{-6} W m ⁻³
Thickness Model	4			6		10		km
Depth of crust	33						km	Andriampenomanana et al. (2017)
Upper Crust (UC)	20.5						km	
Lower Crust (LC)	12.5						km	
Mean A (UC)	1.5						10^{-6} W m ⁻³	Horton et al. (2016)
Mean A (LC)	0.72						10^{-6} W m ⁻³	
A - Total Crust	1.2						10^{-6} W m ⁻³	
Fault Properties	F1; F2							
Aperture	Min.			Mean		Max.		m
D_f	250×10^{-6}			1.1×10^{-3}		2×10^{-3}		
Permeability	10^{-14}			10^{-10}		10^{-7}		m ²
k_f	10^{-14}			10^{-10}		10^{-7}		

271 λ =thermal conductivity, ρ = density, c = heat capacity, A = radiogenic heat production

272 Transient thermal conductivity λ ($\text{Wm}^{-1} \text{K}^{-1}$) and diffusivity α ($\text{m}^2 \text{s}^{-1}$) were measured with
273 the optical scanning method using an infrared scanner developed by LGM Lippmann. The
274 heat capacity, c ($\text{J kg}^{-1} \text{K}^{-1}$), was deduced from the thermal conductivity and thermal
275 diffusivity assessment (Popov et al. 2016; Popov et al. 1999).

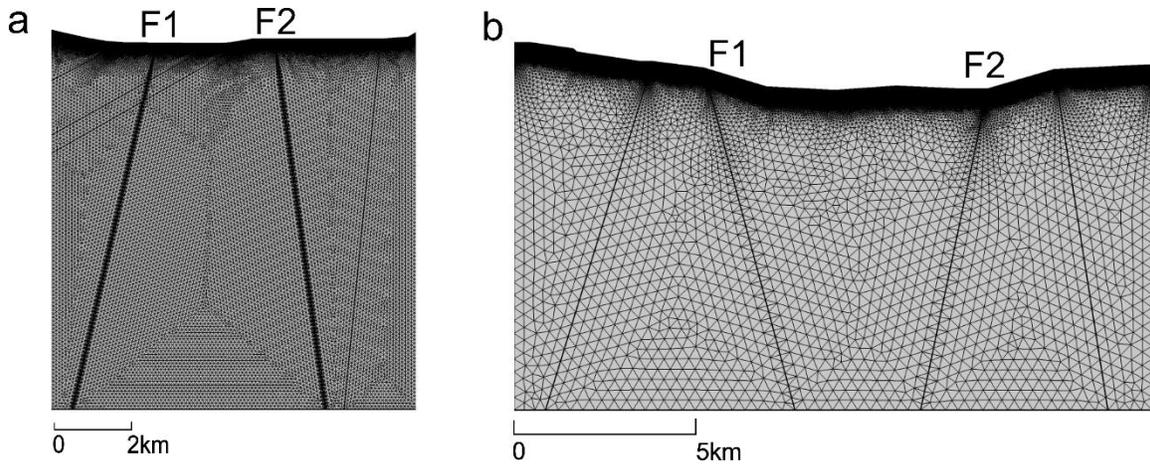
276 The internal radiogenic heat generation (A ; 10^{-6}W m^{-3}) for each rock presented in Table 2
277 was estimated from the concentration of the radiogenic elements U, Th and K, as reported
278 in Rajaobelison et al. (2021).

279 **3.3.3. Fault properties**

280 This study assumed fault aperture and permeability from 250 μm to 0.2 cm and from 10^{-14}
281 to 10^{-7}m^2 , respectively (Table 2). These ranges are based on the literature, taken from
282 various in-situ hydraulic tests performed at geothermal sites (e.g. Holzbecher et al. 2011;
283 Jeong et al. 2001) and examples from numerical simulation studies of groundwater flow in
284 discrete fracture models (e.g. Bisdorn et al. 2016; Guillou-Frottier et al. 2013). The
285 minimum fault aperture range corresponds to that observed under a normal stress of
286 20 Mpa in a laboratory experiment and which validated the cubic law for laminar flow of
287 fluids through open fractures (Witherspoon et al. 1980)

288 **3.4 Mesh**

289 Refinement of the mesh increases from bottom to top and close to the faults to avoid
290 convergence problems. These locations require more accuracy due to large flow and
291 temperature contrasts (Figure 6). A non-structured mesh with triangular elements was used,
292 and the mesh statistics are summarized in Table 3.



293

294 **Figure 6** Finite element mesh of the 2D numerical models for a) the Andavakoera
 295 normal fault zone at the basement-sediment contact in the Ambilobe area, and b) the
 296 Ambanja graben.

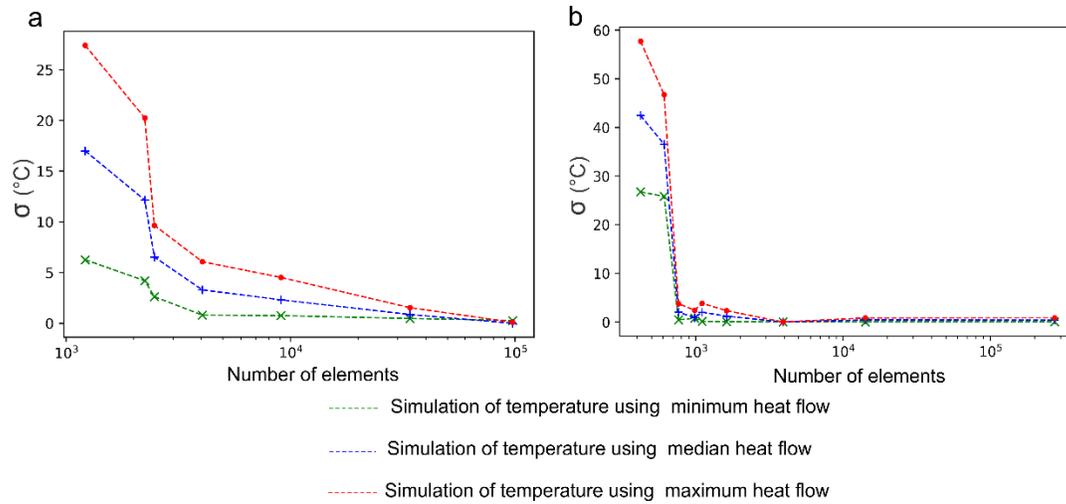
Table 3 Mesh statistics of Ambilobe and Ambanja 2D models

	Ambilobe	Ambanja	Unit
Number of element	101 672	274 403	
Maximum element size	104	404	m
Minimum element size	0.208	0.404	m
Nodes	49 506	137 998	

297 A mesh convergence study was undertaken to verify that the temperature solution is
 298 independent of the element size; i.e., a chosen cutline was sampled uniformly from the
 299 models at different mesh sizes. The parameter σ was then computed according to equation
 300 2:

$$301 \quad \sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (\Delta T_i)^2} \quad (2)$$

302 where N is the sample number, ΔT_i is the temperature variation at depth $x_i=(i-1)D/N-1$ along
 303 the chosen cutline where the mesh size of the model is refined. Here, D is the depth of the
 304 model. It demonstrated that a stable solution was obtained above 10^4 elements with a
 305 difference of about 1°C or less (Figure 7).



306

307 **Figure 7** Mesh convergence study for the a) Ambilobe and b) Ambanja models.

308

3.5 Boundary conditions

309

3.5.1 Groundwater flow conditions

310 Topography-driven groundwater flow affecting forced convection was reproduced by
 311 imposing lateral flow boundary conditions (López and Smith 1995; Smith and Chapman
 312 1983; Tóth 2009; Woodbury and Smith 1985). Without any information about the water
 313 table level, the lateral boundaries of the model are assigned a constant hydraulic head equal
 314 to the topographic elevation (Figure 5). Each segment representing a river in the model
 315 valley is also assigned a constant hydraulic head value equal to its nodal elevation. An
 316 outflow boundary was assigned at the upper-end of the faults to allow fluids to exit at the
 317 upper-end of the faults. The base of the models was assumed impermeable.

318

3.5.2 Heat transfer conditions

319 A constant temperature was specified at the surface of the models and assumed to be a
 320 linear function of the altitude. Equation 3 establishes the relationship between the surface
 321 temperature (T_s) and altitude (z):

$$322 \quad T_s = -0.0046z + 26.85 \quad (3)$$

323 where -0.0046 and 26.85 °C are constants determined from average annual temperatures
 324 measured at four meteorological stations in Madagascar: Antsiranana, Mahajanga,
 325 Antananarivo and Tolagnaro (Table 4; Stalenberg et al. 2018).

Table 4 Data from selected meteorological stations in Madagascar

Station	Antsiranana	Mahajanga	Antananarivo	Tolagnaro
Altitude (m)	105	27	1268	22
Average annual temperature (°C)	24.7	27	19.5	24

326 The lower boundary of the models, at a depth of 10 km, was assigned a second type
 327 condition of constant heat flow (Table 5), defined according to the Curie point depth (CPD;
 328 Tanaka et al. 1999) and the internal heat generation in the crust. Heat flow at the CPD
 329 (Q_{CDP} , mWm^2) was initially calculated using equation 4, which takes into account the
 330 surface ($T_0 = 20$ °C) and Curie ($T_{CDP} = 580$ °C) temperatures:

$$331 \quad Q_{cpd} = \lambda \frac{T_{CPD} - T_0}{Z_{CPD}} - A \frac{Z_{CPD}}{2} \quad (4)$$

332 where A (10^{-6} W m^{-3}) is the average heat generation due to the radioactive decay of
 333 elements in the crust, which is the weighted average of the lower and upper crust heat
 334 generation. The internal heat generation in the upper and lower crusts was estimated at
 335 $1.5 \times 10^{-6} \text{ W m}^{-3}$ and $0.72 \times 10^{-6} \text{ W m}^{-3}$, respectively (Table 2; Horton et al. 2016).
 336 λ ($\text{W m}^{-1} \text{ K}^{-1}$) is the average thermal conductivity of the crust and Z_{CPD} (m) is the CPD.
 337 The range of the CPD was estimated at 10 km to 33 km, corresponding to the average

338 Moho depth in northern Madagascar, using the centroid method of Tanaka et al. (1999)
 339 and according to the available world map of the CPD (Li et al. 2017).

340 The heat flow at 10 km (Q_{10} , mWm^{-2}) was then calculated with:

$$341 \quad Q_{10} = Q_{\text{cpd}} + A_{\text{LC}} H_{\text{LC}} + A_{\text{UC}} (H_{\text{UC}} - H_{\text{model}}) \quad (5)$$

342 where H_{LC} and H_{UC} are the thickness of the lower and upper crusts, respectively, H_{model} is
 343 the thickness of the model, and A_{LC} and A_{UC} are the heat generation of the lower and upper
 344 crusts, respectively (Table 2).

345 Adiabatic heat transfer conditions were applied to the lateral boundaries.

Table 5 Parameters for the heat transfer boundary condition

Parameters	Value			Unit
Surface temperature	$T_s = -0.0046z + 26.85$			$^{\circ}\text{C}$
Heat flow at base (Q_{10})	Min 50	Mean 99	Max 148	mWm^{-2}

346 **3.6 Parameter sensitivity**

347 The sensitivity of the model to the uncertain parameters was evaluated using the parametric
 348 sweep function implemented in COMSOL Multiphysics. The value of the parameters was
 349 set from the minimum to maximum. These parameters are basal heat flow, fault aperture
 350 and fault permeability (Tables 2 and 5). Combining these three parameters with the
 351 different fault dip scenarios (Table 1) yielded 96 simulations for the Ambilobe 2D model
 352 and 81 for Ambanja.

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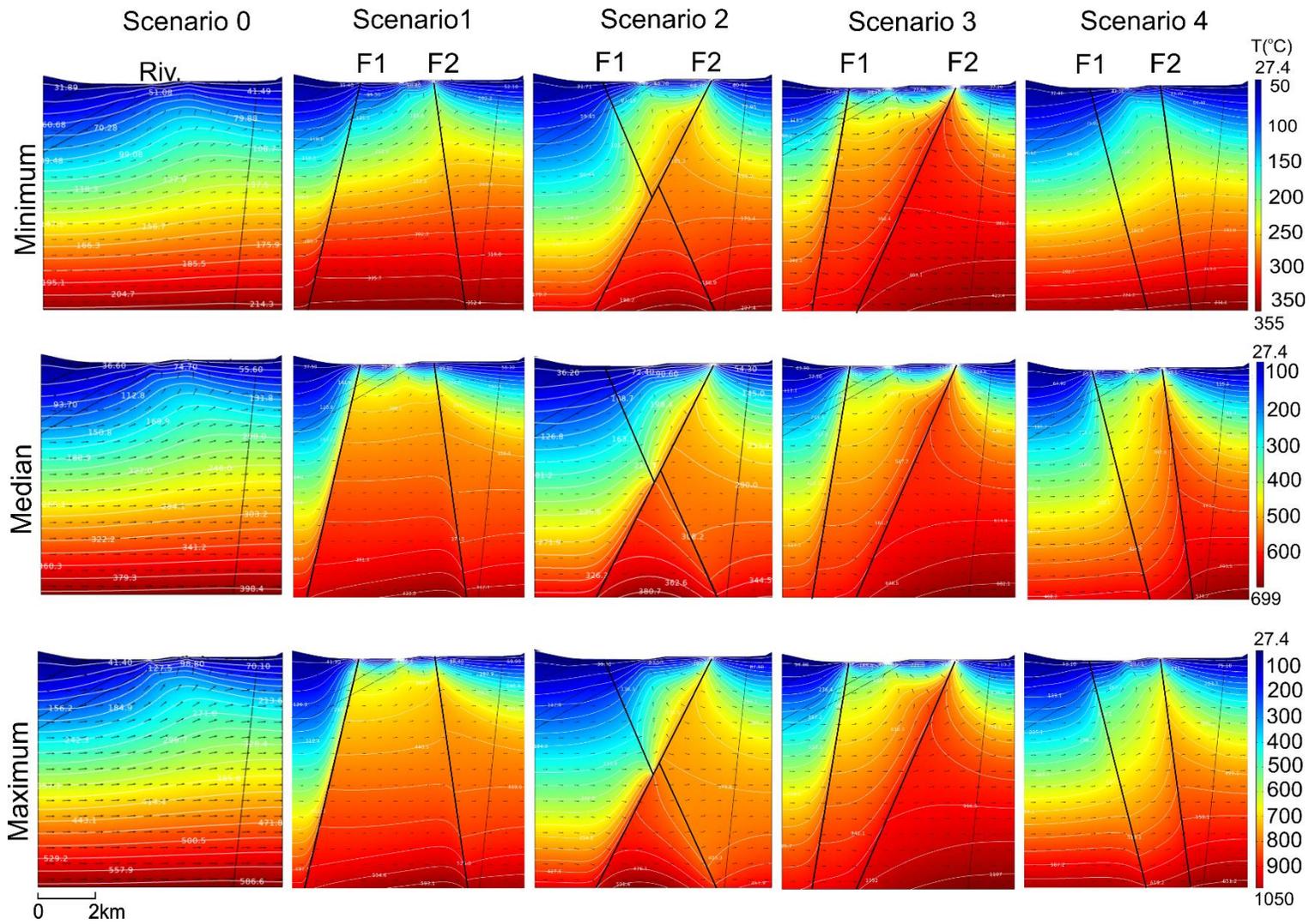
4. Results and analysis

355

4.1 2D subsurface temperature distribution and flow velocity

356 The different scenarios shown in Figures 8 and 10 are for base conditions using minimum,
357 median and maximum heat flow values and average fault properties (Tables 1 and 2). The
358 simulation results confirm that the highest temperatures occur when heat flow is maximum,
359 and that fluids and heat ascend along faults compared the fault-free base case (scenario 0).
360 Temperature profiles as a function of depth along fault lines (Figures 9 and 11) show which
361 simulations best reproduce the near-surface temperature of the hot springs. The results also
362 indicate the depth at which reservoir temperature is attained, assuming the chemical
363 geothermometer provides a reliable reservoir temperature estimate. The most realistic
364 scenarios are when hot spring temperatures are attained near the upper-end of the faults,
365 and the reservoir temperature is at a reasonable depth, below approximately 2 km. The
366 most realistic simulation cases for Ambilobe are maximum heat flow value and fluids rising
367 along fault F2 in scenario 1, maximum heat flow value and fluids rising along fault F1 in
368 scenario 2, and median or maximum heat flow values and fluids rising along fault F2 in
369 scenarios 3 and 4 (Figures 8 and 9).

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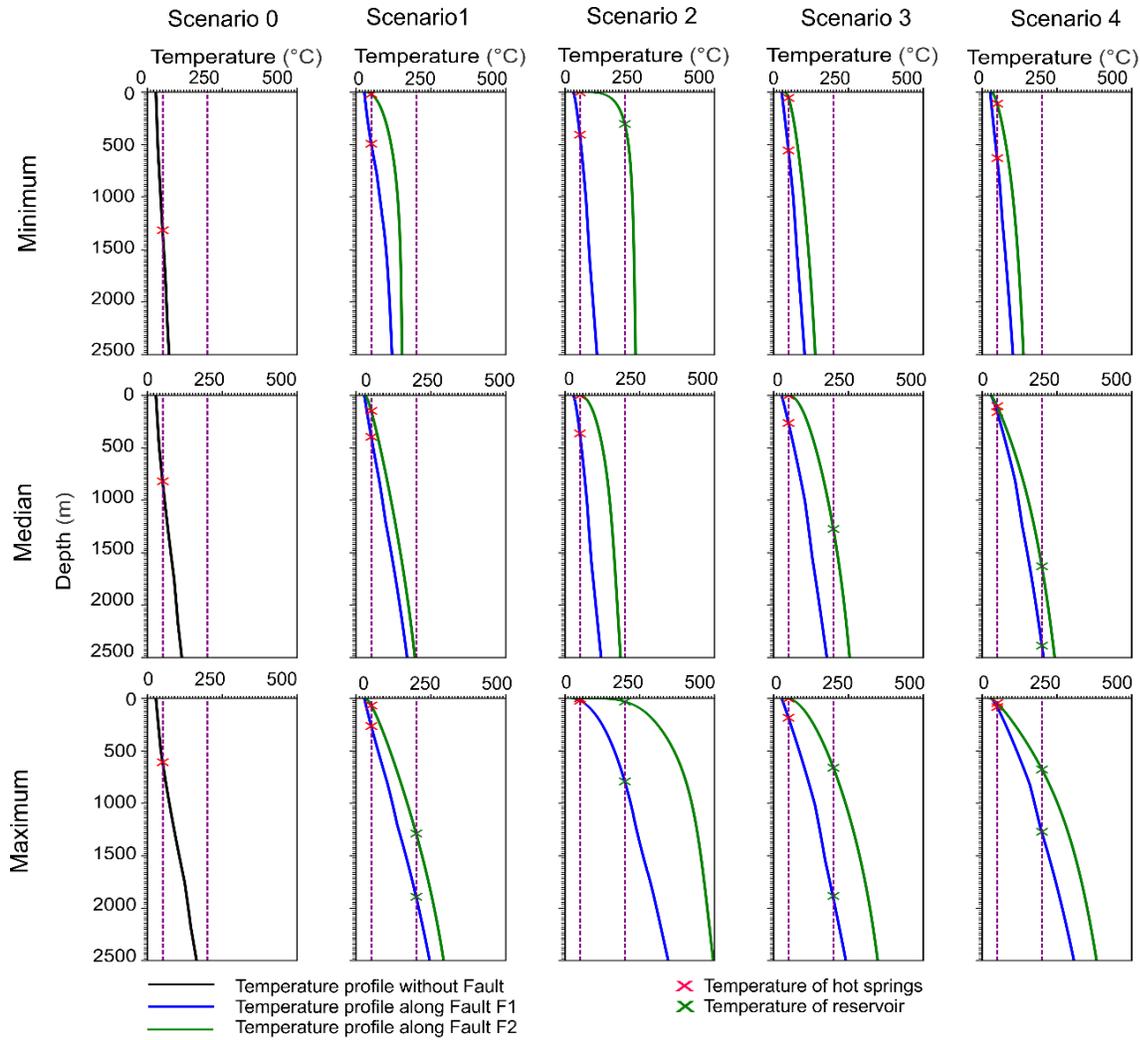


371

372 **Figure 8** Simulated temperature distribution for the Ambilobe 2D model considering different fault dips and heat flux variations

373 at 10 km depth. Black arrows indicate the velocity field and flow direction; white lines are isotherms

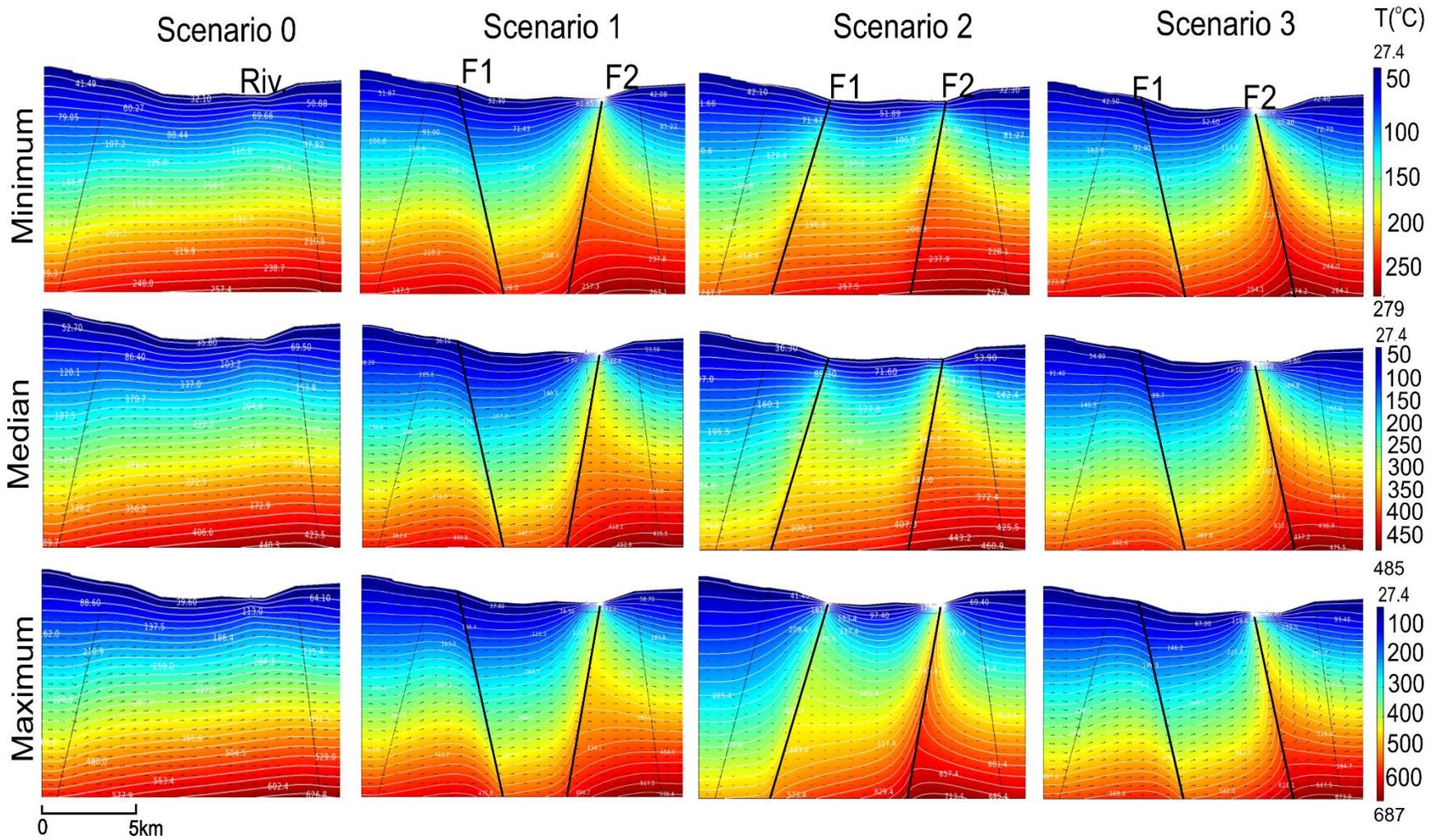
374 The most realistic cases for the Ambanja graben are found in scenario 1 with median and maximum
 375 heat flow values and fluids rising along fault F2 (Figures 10 and 11).



376

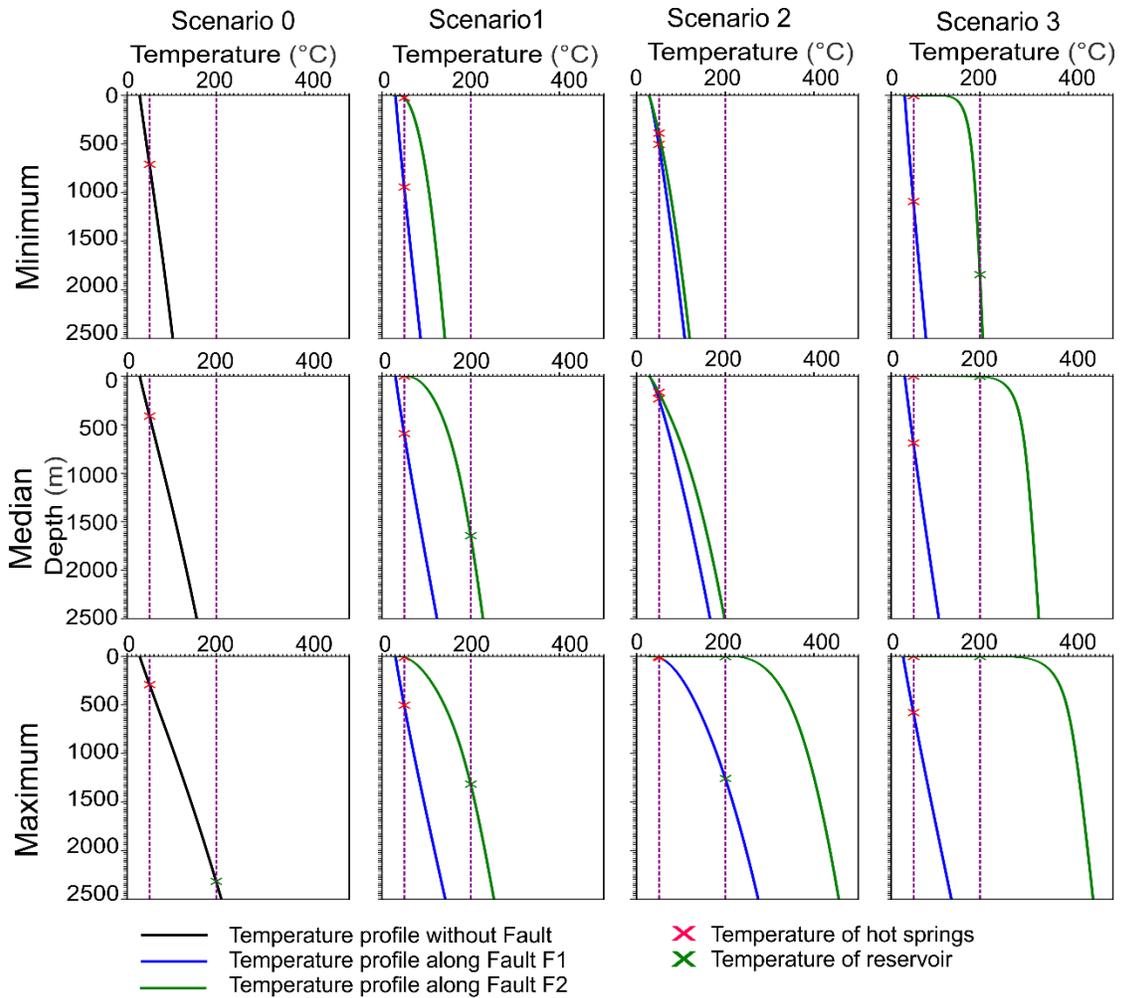
377 **Figure 9** Temperature profiles as a function of depth along fault lines for the Ambilobe 2D
 378 model. The temperature profiles in scenario 0 were obtained from an average cutline drawn in the
 379 fault-free model.

380



381

382 **Figure 10** Simulated temperature distribution for the Ambanja 2D model considering different fault dips and heat flux variations at
 383 10 km depth. Black arrows show the velocity field and flow direction; white lines are isotherms.



384

385 **Figure 11** Temperature profiles as a function of depth along fault lines for the Ambanja
 386 2D model. The temperature profiles in scenario 0 were obtained from an average cutline
 387 drawn in the fault-free model.

388 The magnitude of the Darcy velocity varies between 10^{-9} and 10^{-2} m s^{-1} along the faults
 389 (e.g. Figure 12). The simulated outflow velocity at the upper-ends of favorable faults
 390 (Table 6 and Figure 12) shows no difference or a 1-2 magnitude difference compared to
 391 the measured flow velocity at some hot springs, which varies between 10^{-9} and 10^{-7} m s^{-1}
 392 (Table 6; Gunnlaugsson et al. 1981).

Table 6 Simulated flow velocity at favorable faults for the most realistic scenarios for Ambilobe and Ambanja models

	Ambilobe				Ambanja	
Most realistic scenario	1	2	3 and 4	3 and 4	1	1
Heat flow Q_{10} (mWm^{-2})	Max	Max	Median	Max	Median	Max
Favorable fault	F2	F1	F2	F2	F2	F2
Fault dip	85° SE	60° NW	75° SE and 85° NW	75° SE and 85° NW	80° NE	80° NE
Measured flow at hot springs, (m s^{-1}) (Gunnlaugsson et al. 1981)	1.09×10^{-8} to 1.45×10^{-7}	9.23×10^{-9} to 1.23×10^{-8}	5.45×10^{-9} to 7.27×10^{-8}		4.26×10^{-9} to 2.89×10^{-8}	
Simulated outflow velocity at upper-ends of fault (m s^{-1})	6.47×10^{-7} to 1.21×10^{-6}	7.07×10^{-7} to 1.11×10^{-6}	9.63×10^{-7} and 1.24×10^{-6} to 2.6×10^{-7}	2.14×10^{-7} and 2.72×10^{-7} to 1.24×10^{-6}	2.32×10^{-8} to 1.19×10^{-3}	9.37×10^{-5} to 9.74×10^{-4}

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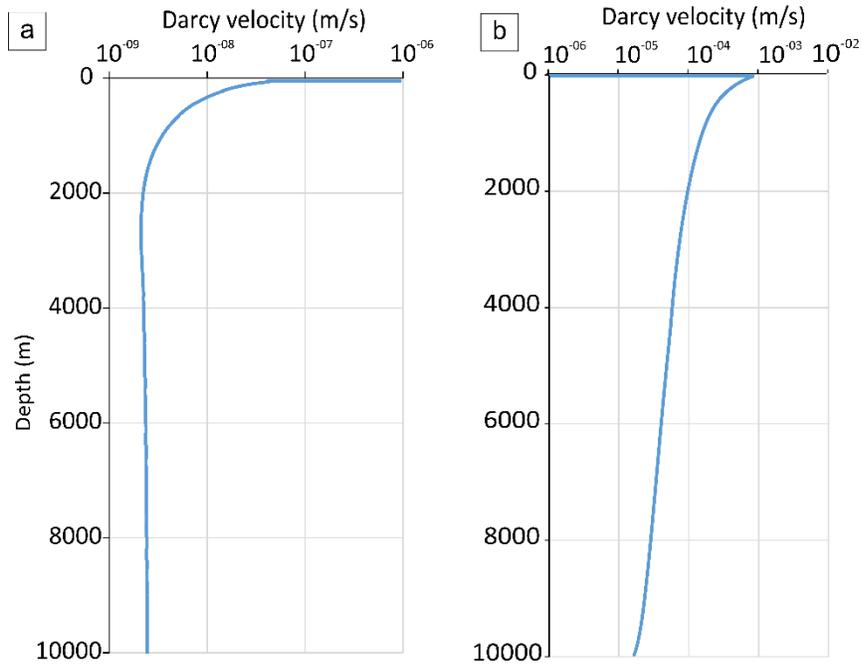
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Figure 12 a) Ambilobe 2D model, scenario 3: flow velocity along fault F2, maximum

402

heat flow value. b) Ambanja 2D model, scenario 4: flow velocity along fault F2, median

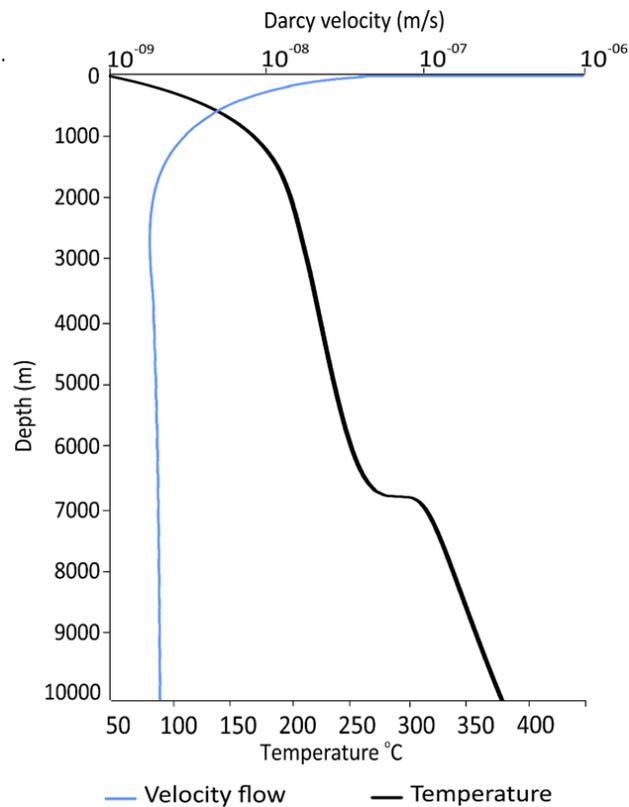
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heat flow value. Results for F1 and F2 use mean aperture and permeability values.

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Figure 13 Variation of simulated flow velocity and temperature as a function of depth along the fault. Ambilobe 2D model, scenario 3, fault F2 and median heat flow value.

417

4.2 Influence of faults

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Faults play a fundamental role in the movement of fluids and pore pressure distribution and therefore exert considerable influence over the temperature distribution. This is evident when comparing scenario 0 (without faults) to faulted scenarios (Figures 8 and 10). The faults serve as conduits for fluid upflow, with Darcy velocity vectors converging upward along the faults toward the hot springs location. The temperature along faults can be up to 150 °C higher than adjacent areas (Figure 8 and 10). Heat transfer becomes conductive in the surrounding host rock, where bulk permeability is lower than the high-permeability zones because fluids drain towards the fault where convection occurs. Faults create

426 permeability heterogeneities in the crust, which affect fluid flow and convective heat
427 transfer, thereby influencing the location of hot springs (Faulds et al. 2010; Faulds and
428 Hinz 2015), especially at their intersections (Belgrano et al. 2016; Person et al. 2012). This
429 is consistent with the numerical modeling of deep fluid flow associated with crustal-scale
430 normal faults in the south-central Canadian Cordillera (Ferguson et al. 2009). The latter
431 reported that the permeability contrasts between host-rocks and faults acting as conduits
432 for preferential fluid flow, have the greatest influence on the subsurface temperature
433 distributions consistent with observed thermal springs. However, the presence of a fault
434 does not necessarily imply the formation of a hot spring unless the favorable conditions are
435 present that allow fluids and heat to ascend and reach the surface (e.g. López and Smith
436 1995; Thiébaud 2008)

437 Simulation scenario 3 for the Ambilobe 2D model clearly illustrates favorable conditions
438 for fluid ascension, with higher simulated temperatures near the upper-end of both faults
439 (Figure 8; Table 1) and fault dips of $< 90^\circ$ facing the fluid flow. As shown in Figure 13,
440 the fluid at the surface, reaches the highest Darcy velocity (10^{-6} m s^{-1}) which match the
441 temperature of the hot spring (50°C). A flow velocity of 10^{-8} m s^{-1} is found at the depth
442 having the reservoir temperature of 180°C .

443 On the other hand, if the fault is facing away from the fluid flow direction, like F1 in
444 scenarios 1 and 3 for the Ambanja graben model (Figure 10; Table 1), then the hydraulic
445 gradient between both ends of the fault is smaller and the simulated temperature near the
446 upper-end of the faults is lower. Similar results were reported by Moreno et al. (2018), who
447 simulated the impact of faults on the circulation of fluids originating from the basement
448 underlying the Nevado del Ruiz volcanic complex of Colombia, where hot springs are

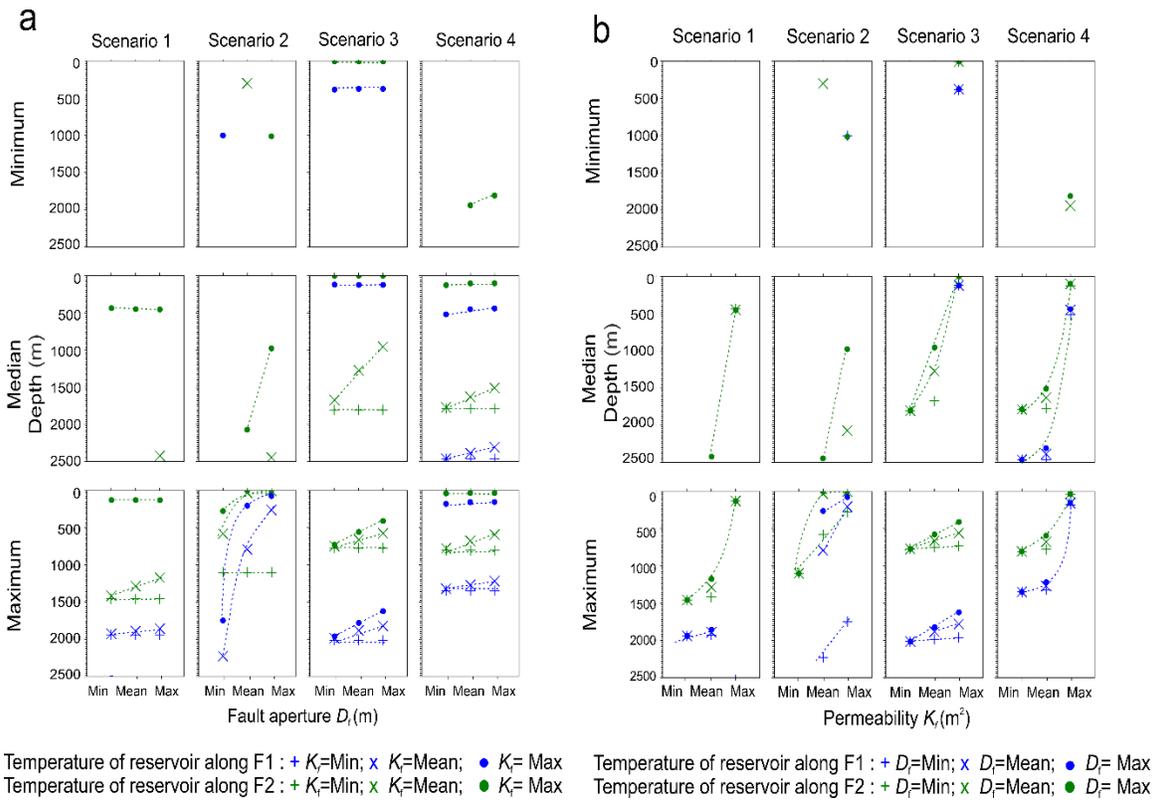
449 present. However, scenarios 1 and 2 for the Ambilobe 2D model showed that fluids are
450 able to rise to the surface along a fault with a dip facing away from the fluid flow direction
451 (F2 and F1, respectively) if it is close to a river that acts as a discharge zone (Figure 8 and
452 9). This is also seen in scenario 4. It suggests that both the fault dip and its distance from a
453 discharge zone where the hydraulic head can be low are important characteristics in favor
454 of fluid ascension.

455 Additionally, convective heat transfer along faults implies that ascending fluids are diluted
456 as they mix with groundwater of shallower origin, to the degree that half of the ascending
457 fluids will reach the upper 75 % of the fault length (Ferguson et al. 2009). This can explain
458 the finding of significant mixing of geothermal fluids with shallower groundwater
459 (Giggenbahr diagram of Figure 5) and the absence of boiling hot springs in the Ambilobe
460 and Ambanja geothermal fields due to cooling along the fault between the reservoir depth
461 and the surface.

462 **4.3 Parameter sensitivity**

463 For each scenario, we investigated the variation in depth at which reservoir temperature is
464 attained as a function of basal heat flow, fault aperture and permeability (Figures 15 and

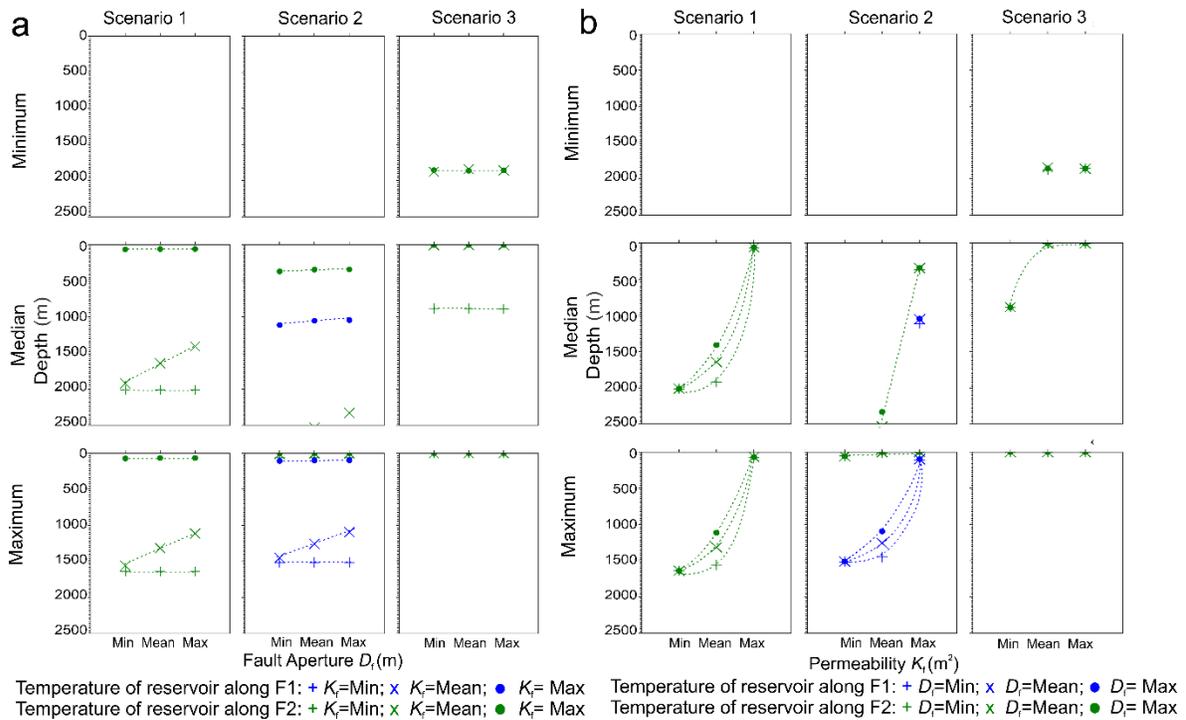
465 16).



467 **Figure 14** Depth variation of reservoir temperature along fault lines in the Ambilobe
 468 2D model according to different fault dip scenarios a) as a function of heat flow and fault
 469 aperture, and b) heat flow and fault permeability. The dotted line indicates the trend of
 470 depth variation.

471 The results reveal that the depth of reservoir temperature decreases with increasing heat
 472 flow, fault aperture and fault permeability. For example, in scenario 1 (Figure 14a), with
 473 the minimum fault aperture (D_f) value and maximum fault permeability (k_f), the depth of
 474 reservoir temperature decreases from >2500 to 200 m along fault F2 when heat flow
 475 increases from the minimum to the maximum. For the same scenario, using maximum heat
 476 flow and mean fault permeability, the depth of reservoir temperature decreases from 1400
 477 to 1100 m along fault F2 by increasing the value of fault aperture. In scenario 3 (Figure

478 14b), using minimum fault permeability and maximum fault aperture, the depth of reservoir
 479 temperature decreases from >2500 to 750 m along fault F2 as function of the heat flow
 480 value. For the same scenario, using maximum heat flow and mean fault permeability, the
 481 depth of reservoir temperature decreases from 800 to 400 m along fault F2 by increasing
 482 the fault aperture. The least favorable cases in scenarios 1 and 2 are when minimum heat
 483 flow fails to produce any points on the plots because the reservoir temperature is always
 484 deeper than 2500 m despite increases in fault aperture and permeability.



486 **Figure 15** Depth variation of reservoir temperature along fault lines in the Ambanja
 487 2D model according to different fault dip scenarios a) as a function of heat flow and fault
 488 aperture, and b) as a function of heat flow and fault permeability. The dotted line indicates
 489 the trend of depth variation.

490 The parameter sensitivity trend described for different fault dip scenarios in the Ambilobe
 491 model is the same for the Ambanja model (Figure 15). The least favorable cases correspond

492 to scenarios 1 and 2 using the minimum heat flow value because the reservoir temperature
493 is deeper than 2500 m despite increasing fault aperture and permeability.

494 We assessed the influence of basal heat flow, fault aperture and fault permeability given
495 the uncertainty associated with those inputs. Varying any of these parameters results in
496 significant differences in pressure, velocity and field temperature, enhancing or
497 diminishing fluid pathways along the fault.

498 The basal heat flow used in our models provides a first estimation of the heat flow range
499 for the geothermal region in northern Madagascar, which is comparable to the known heat
500 flows of the proposed analogue geothermal systems for Ambilobe and Ambanja discussed
501 below (Rajaobelison et al. 2020). In zones of extension and continental rifting, regional
502 heat flow estimates are high, generally from 75 to 125 mWm^{-2} (Jaupart et al. (2015)). The
503 range of heat flow for the Great Basin (USA) is from 50 to $\sim 120 \text{ mWm}^{-2}$, averaging roughly
504 90 mWm^{-2} (Blackwell D and Richards 2004). In Western Turkey, particularly in the Gediz
505 graben, the heat flow varies from ~ 50 to 140 mWm^{-2} , with values exceeding $\sim 100 \text{ mWm}^{-2}$
506 (Yilmazer et al. 2010). In the present study, the basal heat flow affects the temperature
507 distribution at depth and thus influences the geothermal gradient along permeable faults
508 (Figure 9, 8 and 10, 11). Moreover, a higher basal heat flow amplifies the convective
509 regime when the fault permeability also increases (López and Smith 1995). In turn, the
510 reservoir temperature is reached at shallower depths. However, the thermal spring
511 distribution does not appear to be a function of heat flow. Indeed, high heat flow is
512 associated with higher temperatures near the upper-ends of the fault, while hot spring
513 temperatures can be found near the upper-ends of the fault in any of the favorable fault
514 scenarios regardless of heat flow (Figures 2).

515 Fault aperture impacts heat transfer along the fault, which is amplified when fault
516 permeability is high ($k_f > 10^{-14} \text{ m}^2$), allowing for fluid ascension as shown in scenarios 1
517 and 2 for the Ambilobe 2D model of Figure 14a. Indeed, a small fault aperture
518 ($D_f > 250 \text{ }\mu\text{m}$) combined with a moderate to high fault permeability (10^{-10} - 10^{-7} m^2) allows
519 hot fluids to be found at shallow depths, $< 2 \text{ km}$ from the surface. Increasing fault
520 permeability shifts the system from petrothermal to transitional, thereby making this
521 parameter a critical factor in numerical models. By varying fault permeability in the model,
522 the transmissivity to flow along faults becomes significant when fault permeability is
523 higher than 10^{-14} m^2 , attracting hot upwelling fluids at depth (Figure 14b and 15b). An
524 optimum combination of country-rock (host rock) and fault permeabilities is also needed
525 to obtain subsurface temperature distributions consistent with observed thermal springs
526 (Forster and Smith 1989). This means, the permeability difference between the country
527 rock and the fault can increase or decrease springs temperatures (Ferguson et al. 2009;
528 Forster and Smith 1989; López and Smith 1995). In the present study, a permeability
529 difference of 4 to 7 orders of magnitude between the country rock and the fault depresses
530 the thermal field. The decrease is due to the downward flux of recharge water, while high-
531 temperature discharge associated with upward flow occurs along the fault plane. In fact,
532 the pressure that forces the water to the surface is mainly supplied by the difference in
533 elevation between the recharge and discharge areas.

534 However, it is well known that fractures and faults can seal and re-open over time through
535 multiple tectonic constraints (e.g. Ingebritsen and Manning 2010). The current seismicity
536 (magnitude $M_w > 5$ in the study areas; (Bertil and Regnault 1998) suggests that faults may
537 maintain efficient permeability over time.

538 5. Discussion

539 5.1 Groundwater flow boundary conditions

540 The hydraulic head applied to the lateral boundaries of the model reproduces topography-
541 driven groundwater flow from NNE to SSE in the Ambilobe model and from NW to SE in
542 the Ambanja model. Surface recharge is neglected since the goal is to evaluate the impact
543 of faults intercepting the regional flow path. At the river segment, the flow vectors are
544 directed toward the surface and the river constitutes a discharge zone (Figures 8 and 10).
545 The magnitude of ascending flow vectors increases from 10^{-10} to 10^{-2} m s⁻¹ when faults
546 intercept ascending flow vectors. The impact of the regional flow path was previously
547 highlighted by Taillefer et al. (2018), who suggested that topography (i.e., an elevated
548 water table) is the key factor controlling fluid pathways and the hot spring distribution in
549 the Têt hydrothermal system of the Eastern Pyrénées in France. Similar conclusions can be
550 made for Ambilobe and Ambanja, where the topography-driven groundwater flow affects
551 forced convective heat transfer along the faults. The flow lines within the models show that
552 the fluids originating from higher elevations reach considerable depth where they can be
553 heated and redirected towards the surface through permeable faults (Figures 8 and 10). This
554 also confirms that hydraulic heads and hydrological budgets control the regional
555 groundwater flow systems in an extensional domain geothermal play, as mentioned by
556 Moeck (2014).

557 5.2 Model limitations

558 As a first step, a simplified model is necessary to understand the flow and heat transfer
559 mechanisms influencing the temperature distribution in a geothermal system where crustal-

560 scale faults control the fluid migration pathway. Fault and host rock permeabilities are
561 assumed constant with depth, although they can decrease with increasing confining
562 pressure (Rajaobelison et al. 2021). With this assumption, forced convection versus
563 conduction is clearly favored. Indeed, permeability probably decreases with depth in the
564 basement due to the contrasting mechanical properties of the minerals present in the rocks,
565 such as mica and feldspar, and in faults due to sealing by the mineral precipitation (Stober
566 and Bucher 2015).

567 The scarcity of structural information in the study area is an important limitation to the
568 models. More structural field data, including dip angle and fracture density measurements,
569 would better constrain the fault dip, aperture and permeability values in the numerical
570 models. Moreover, statistical features summarized from field data are needed for the
571 stochastic processes in discrete fracture models (e.g. Ivanova et al. 2014). It is currently
572 difficult to anticipate fracture behavior at depth. Ggeophysical surveys (e.g. gravity and
573 magnetotellurics) would help to image deep structures, build more accurate 2D models,
574 and eventually develop 3D models around faults.

575 Even though these aspects limited our modeling approach, the present work successfully
576 reproduces hot spring temperatures observed at surface, with consistent reservoir
577 temperatures at reasonable depths.

578 **5.3 Geothermal exploration**

579 This study identified favorable fault characteristics that trigger fluid ascension and favor
580 the formation of geothermal energy sources, knowledge that can assist geothermal
581 exploration efforts to better identify exploration targets. More specifically, the target

582 should be normal faults with $< 90^\circ$ dips facing the regional fluid flow path driven by
583 topography. Fault permeability must be higher than the host rock, corresponding to the
584 critical range of permeability under which forced convection occurs, combined with a
585 minimum aperture of 250 μm .

586 The simulation results also revealed that an average drilling depth of 1 to 2 km along
587 favorable faults should reach the temperature interval of 150–200 $^\circ\text{C}$ (Figures 8 and 10).
588 This finding can positively impact an exploration project since drilling cost increases
589 nonlinearly with depth (e.g. Augustine et al. 2006).

590 **6. Conclusions**

591 This study presents, for the first time, 2D numerical models simulating groundwater flow
592 and heat transfer according to a realistic topography and fault hypothesis in Madagascar.
593 The aim is to better understand heat transfer mechanisms involved with the geothermal
594 systems of the Ambilobe normal fault zone and Ambanja graben in northern Madagascar.
595 Numerical simulations are used to define the large-scale temperature field in such
596 extensional-type geothermal systems. The resulting simulated temperature distribution
597 appears to be characteristic of conductive heat transfer in a low-permeability rock matrix
598 and forced convective heat transfer along faults, representing favorable conditions that
599 facilitate fluid ascension. The most realistic scenarios are when the hot spring temperature
600 is attained near the upper-end of the fault and the reservoir temperature is at a reasonable
601 depth, shallower than ~ 2 km. The simulated flow velocity at the upper-ends of faults is
602 comparable to those measured in surface hot springs.

603 Our findings support previous interpretations of conceptual models in northern
604 Madagascar, where conduction is the dominant heat transfer mechanism in low-
605 permeability rock matrix, except along faults that experience a strong hydraulic gradient
606 and provide a path for fluids to rise with forced convective heat transfer as the dominant
607 mechanism

608 Numerical models used in this study can be a predictive tool to help define geothermal
609 exploration strategies in similar normal fault zone and graben settings. Further
610 hydrogeological assessment using stable isotope analyses on springs and groundwaters can
611 help improve and support the simulated fluid circulation concept by defining infiltration
612 altitudes and determining fluid origin. Deep borehole data, such as temperature logs, will
613 also be required for the next steps to realistically constrain the temperature prediction and
614 advance geothermal exploration in North Madagascar.

615 **Author contributions**

616 MR: Data collection, investigation, conceptualization, methodology, Writing (original
617 draft preparation), formal analysis. JR and MM: Supervision, resources, project leads. JR,
618 CD and MR: Validation. JR, MM, CD and SL: Drafting and editing. All authors reviewed
619 the manuscript and have read and agreed to the published version of the manuscript.

620 **Competing interests**

621 The authors declare that they have no competing interests.

622 **Availability of data and materials**

623 The relevant datasets analyzed in this study are all presented in the manuscript.

624 **Acknowledgments**

625 The authors would like to thank the Canadian Francophonie Scholarship Program CFSP,
626 which supported the first author with a scholarship. The UNESCO International geoscience
627 program (IGCP) is also acknowledged for providing a framework that supported
628 collaboration among the members of the IGCP-636 group involved in geothermal research
629 and who participated as coauthors to this paper. Additional thanks go to Elie R. for
630 discussions and invaluable help with modeling issues using COMSOL.

631 7. References

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- 861

Author's contribution:

MR: Data collection, Investigation, Conceptualization, Methodology, Writing - Original
Draft preparation, formal analysis.

JR and MM: Supervision, Resources, led the project;

JR, CD and MR: Validation.

JR, MM, CD, and SL: Drafting - Reviewing and Editing.

All authors reviewed the manuscript, have read and agreed to the published version of the
manuscript.