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

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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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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 $>10^{-14}\,\mathrm{m}^2$. 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} m^2, 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.

2. Geological setting and geothermal context

2.1 Tectonic framework and regional fault system

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

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

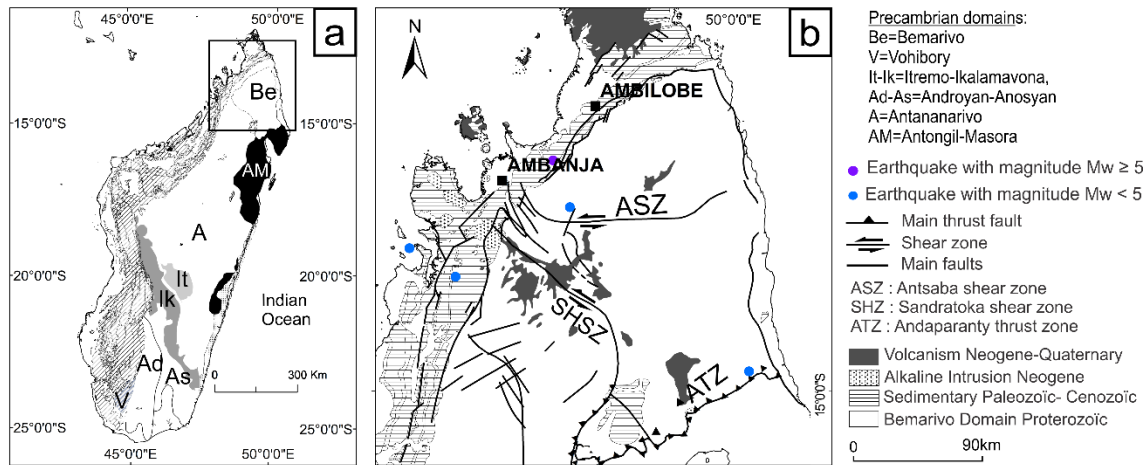137 Montagne d'Ambre, in the extreme north of Madagascar (Chorowicz et al. 1997)

138

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).
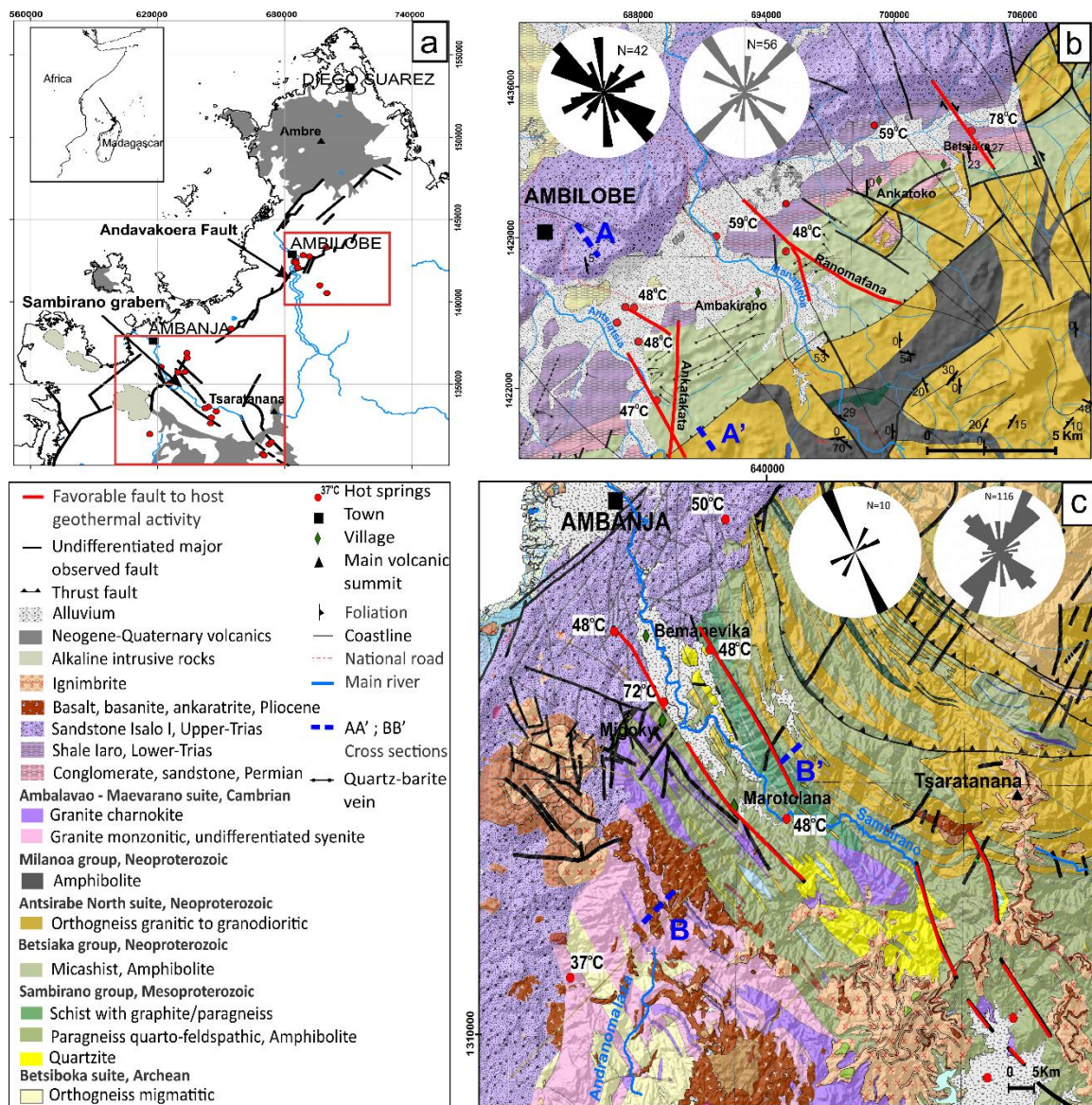
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Figure 2　　(a) Location of the Ambilobe and Ambanja geothermal areas. (b) and (c) Detailed geology of each area (modified from Roig et al. 2012). The rose diagrams illustrate the major fracture trends (in black) established from field data collected in 2018 and the major faults trends (in grey) established from the map data of Roig et al. (2012).
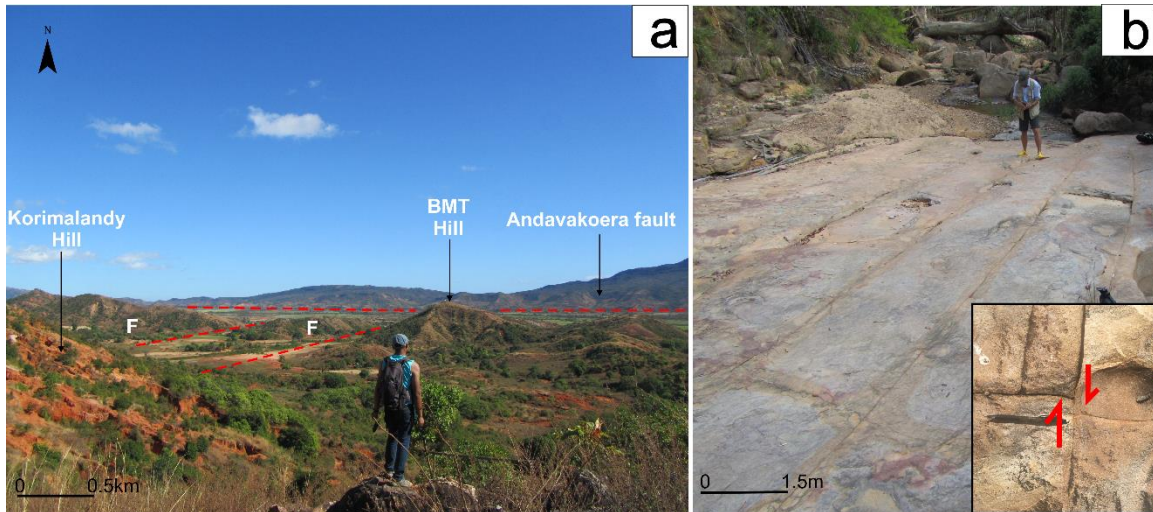
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Figure 3: a) Field view of the Andavakoera fault line and its conjugated faults (F). b) Metric fractures in the Ambanja sandstone formation with close-up illustrating fracture movements.

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

Using chemical geothermometers (Gunnlaugsson et al. 1981) and the Giggenbah diagram (Figure 4), the reservoir temperatures in the Ambilobe and Ambanja areas are expected to be 140 and 200 °C, respectively.
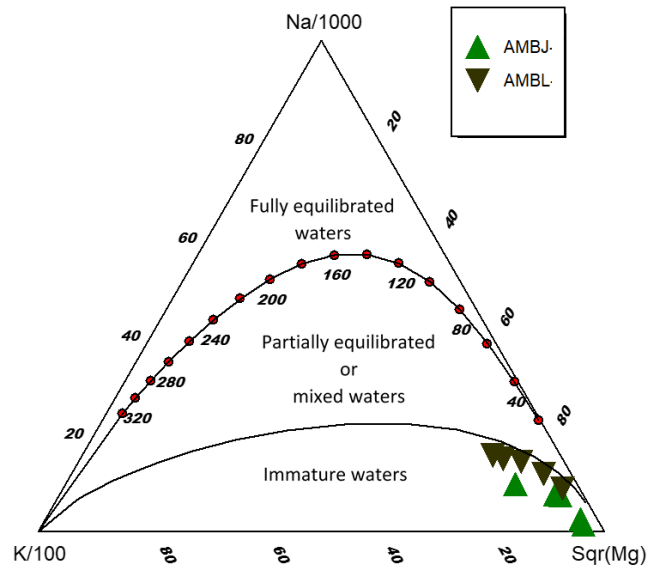
Figure 4: Chemical composition of waters from the Ambilobe (AMBL) and Ambanja (AMBJ) hot springs plotted on a ternary Na-K-Mg diagram (Giggenbach 1988). The Na, K, Mg concentrations were reported in Gunnlaugsson et al. (1981).

2.3 Lithosphere structure and geological formations

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

The geological formations of the Ambilobe and Ambanja areas and their thermo-hydraulic properties have been described in Rajaobelison et al. (2020); and Rajaobelison et al. (2021). The Permo-Triassic sedimentary rocks of the Ambilobe Basin, overlying the Proterozoic 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.
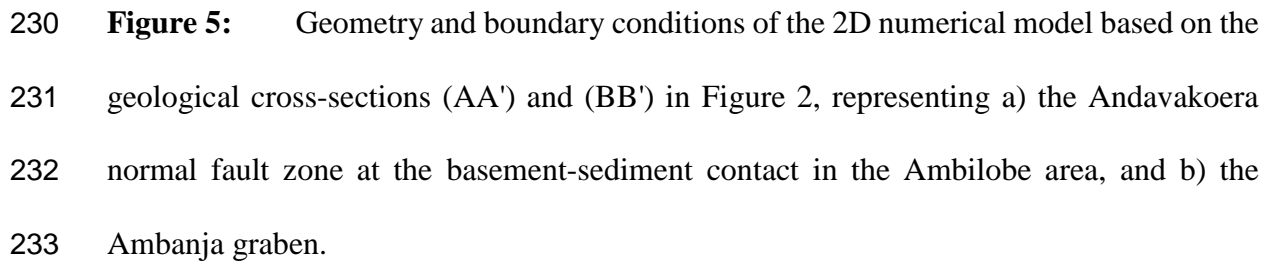
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Figure 5: Geometry and boundary conditions of the 2D numerical model based on the geological cross-sections (AA') and (BB') in Figure 2, representing a) the Andavakoera normal fault zone at the basement-sediment contact in the Ambilobe area, and b) the Ambanja graben.

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Table 1   Fault scenarios

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

248   where λ_b $(Wm^{-1}K^{-1})$ is   the   bulk   thermal   conductivity; T (°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 (J kg^{-1} 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					Ambanja			
Formation	Sediments			Basement		Basement			
Geological Units	Permian Sandstone	Eo Triassic shale	Triassic sandstone	Mica Shist Amphibolite	Ortho-gneiss	Syenite	Para-gneiss		
Mean $\varnothing$	0.07	0.08	0.07	0.11	0.05	0.001	0.02	Fractional	Rajaobelison et al. (2021)
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}	
Mean A (LC)	0.72								Horton et al. (2016)
A- Total Crust	1.2							10^{-6} W m^{-3}	
Fault Properties	F1; F2								
Aperture		Min.		Mean		Max.		m	Current study
D_f		250×10^{-6}		1.1×10^{-3}		2×10^{-3}			
Permeability		10^{-14}		10^{-10}		10^{-7}		m^2	
k_f									

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

272 Transient thermal conductivity λ (Wm^{-1} K^{-1}) and diffusivity α (m^2 s^{-1}) were measured with

273 the optical scanning method using an infrared scanner developed by LGM Lippmann. The

274 heat capacity, c (J kg^{-1}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).

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. Bisdom 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)

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.
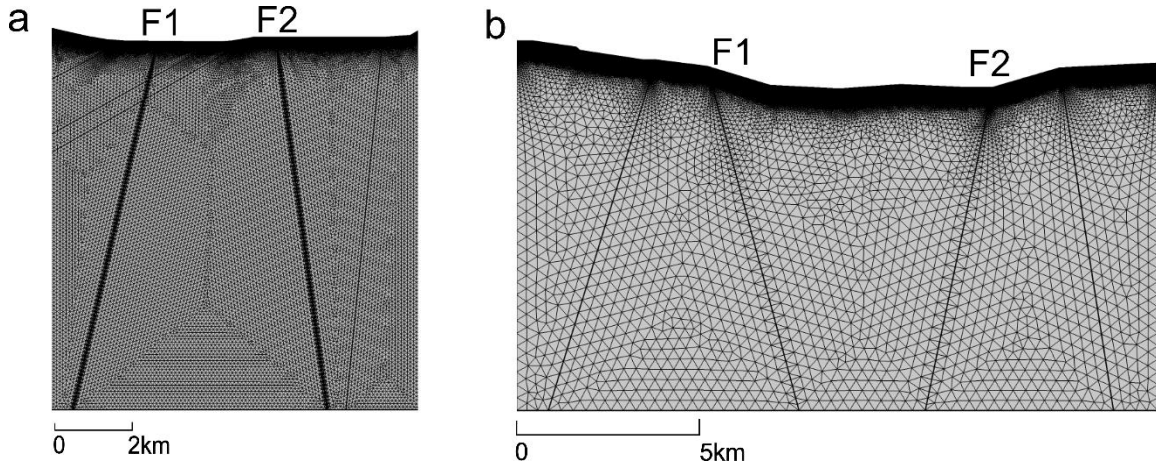
293

0 2km

0 5km

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

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

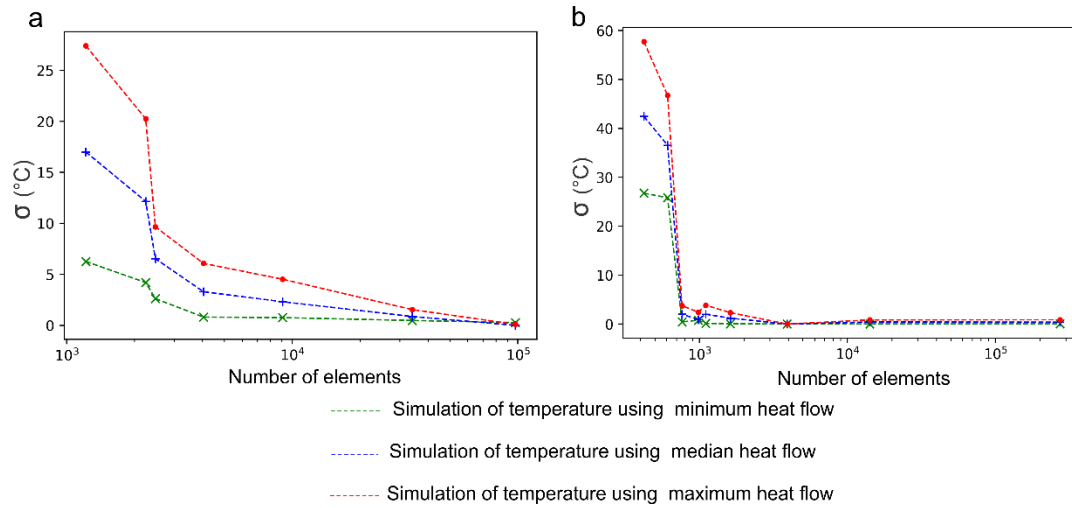305 difference of about 1 °C or less (Figure 7).

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

3.5 Boundary conditions

3.5.1 Groundwater flow conditions

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

322           $T\text{s} = -0.0046z + 26.85$ (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           $Q_{cpd} = \lambda \frac{T_{CPD} - T_0}{Z_{CPD}} - A \frac{Z_{CPD}}{2}$ (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   1.5×10^{-6} W m^{-3} and 0.72×10^{-6} W m^{-3}, respectively (Table 2; Horton et al. 2016).

336   λ (W m^{-1} 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$$Q_{10} = Q_{\text{cpd}} + A_{\text{LC}} H_{\text{LC}} + A_{\text{UC}} (H_{\text{UC}} - H_{\text{model}})$$(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	$T_S = -0.0046z + 26.85$			ºC
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.

353

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
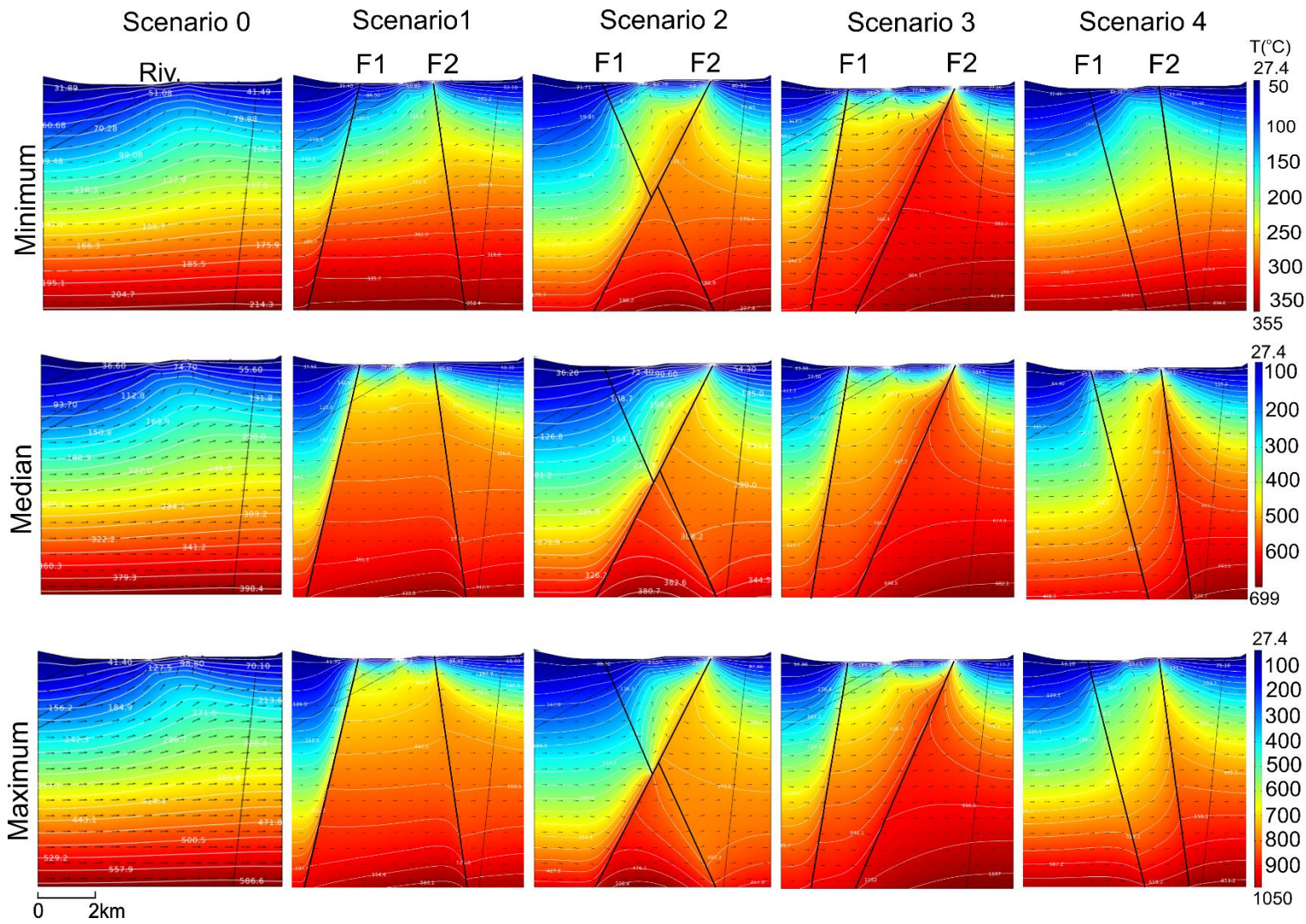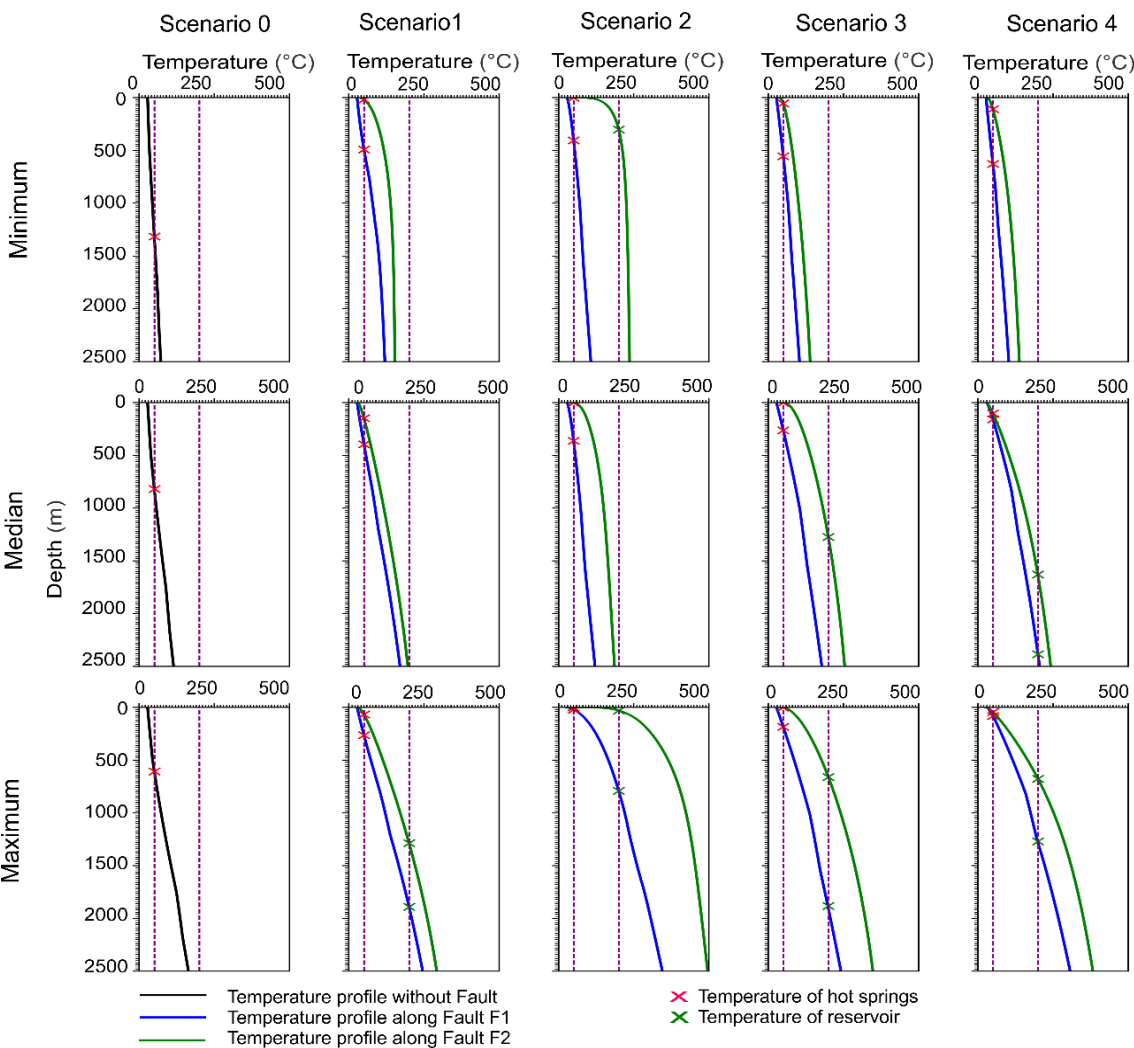
369   scenarios 3 and 4 (Figures 8 and 9).

370

Figure 8   Simulated temperature distribution for the Ambilobe 2D model considering different fault dips and heat flux variations 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
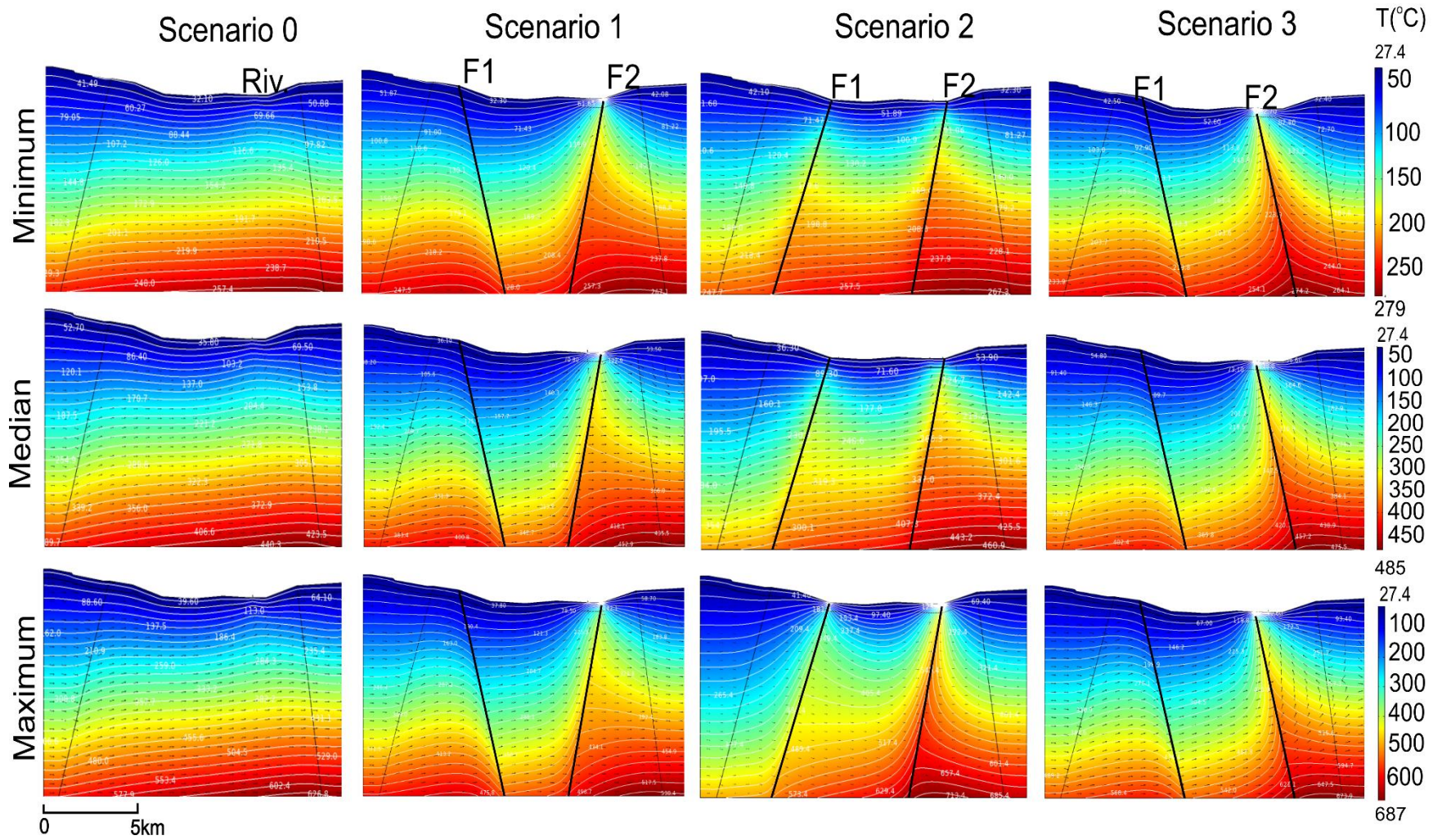
379   fault-free model.

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.
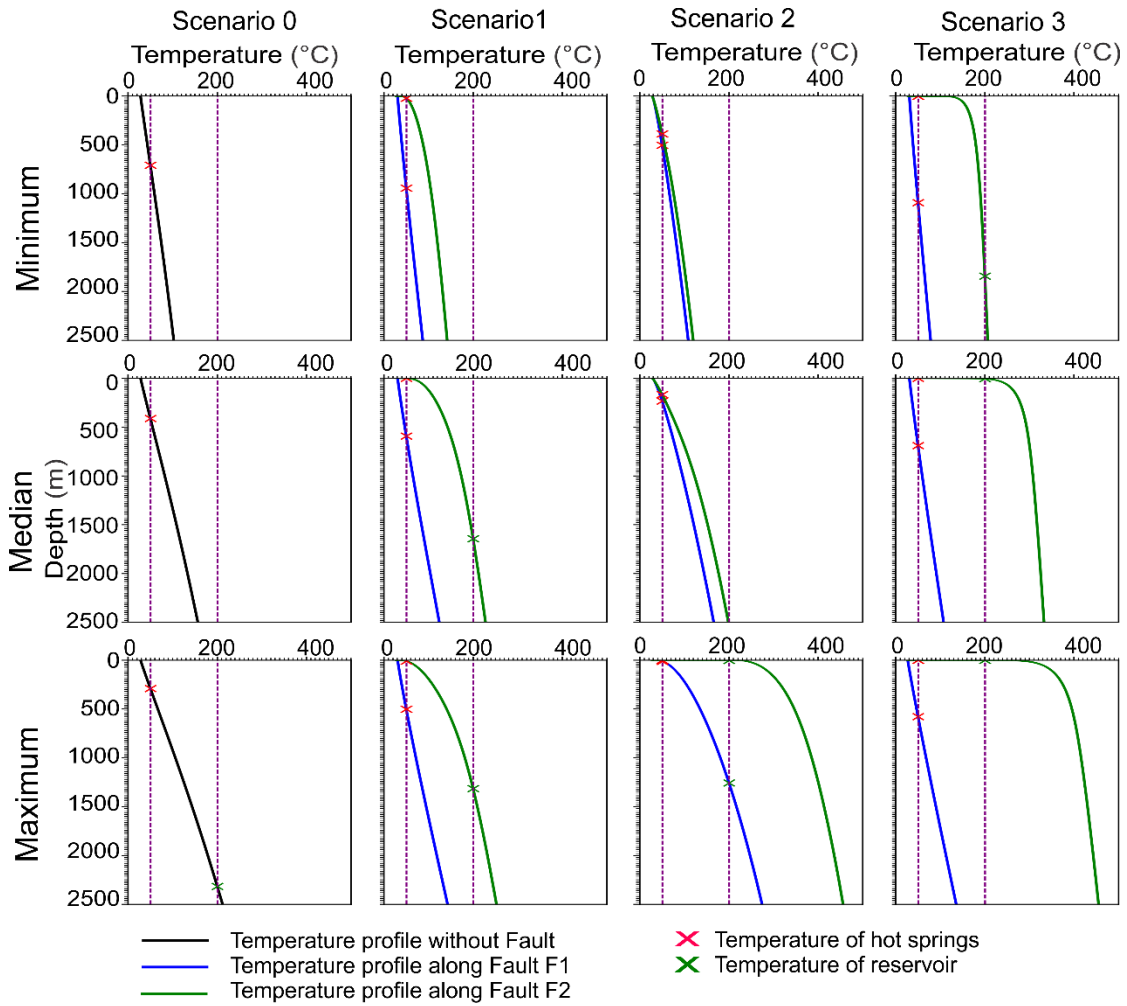
Figure 11 Temperature profiles as a function of depth along fault lines for the Ambanja

2D model. The temperature profiles in scenario 0 were obtained from an average cutline

drawn in the fault-free model.

The magnitude of the Darcy velocity varies between 10^{-9} and 10^{-2} m s^{-1} along the faults

(e.g. Figure 12). The simulated outflow velocity at the upper-ends of favorable faults

(Table 6 and Figure 12) shows no difference or a 1-2 magnitude difference compared to

the measured flow velocity at some hot springs, which varies between 10^{-9} and 10^{-7} m s^{-1}

(Table 6; Gunnlaugsson et al. 1981).

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

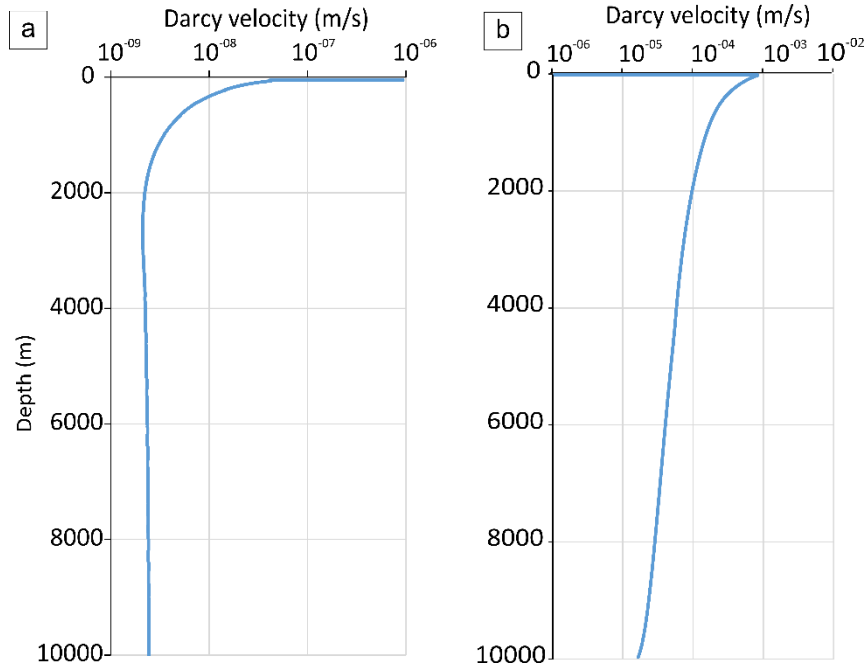|	Ambilobe				Ambanja	
Most realistic scenario	1	2	3 and 4	3 and 4	1	1
Heat flow Q_{10} (mWm^{-2})	Max	Max	Median	Max	Median	Max
Favorable fault	F2	F1	F2	F2	F2	F2
Fault dip	85° SE	60° NW	75° SE and 85° NW	75° SE and 85° NW	80° NE	80° NE
Measured flow at hot springs, (m s^{-1}) (Gunnlaugsson et al. 1981)	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}

Figure 12   a) Ambilobe 2D model, scenario 3: flow velocity along fault F2, maximum heat flow value. b) Ambanja 2D model, scenario 4: flow velocity along fault F2, median heat flow value. Results for F1 and F2 use mean aperture and permeability values.
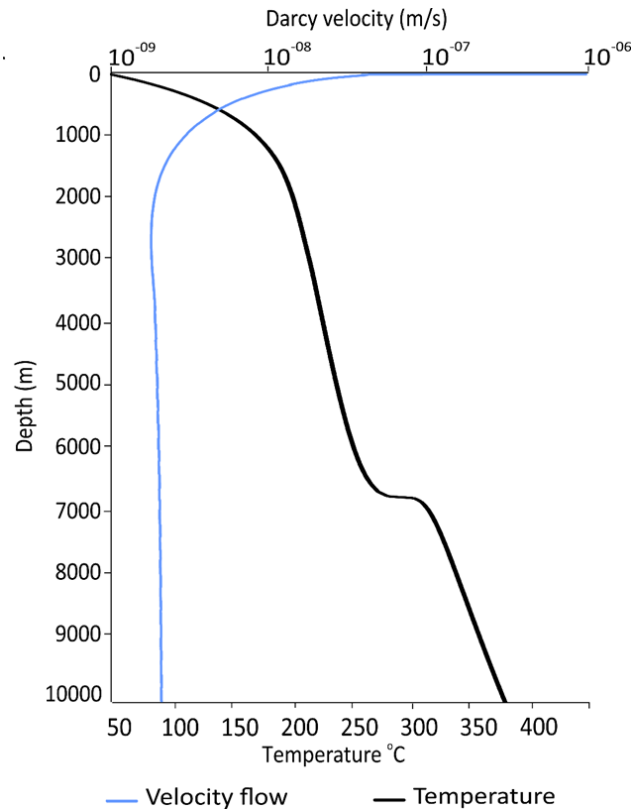
Figure 13 Variation of simulated flow velocity and temperature as a function of depth along the fault. Ambilobe 2D model, scenario 3, fault F2 and median heat flow value.

4.2 Influence of faults

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° 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

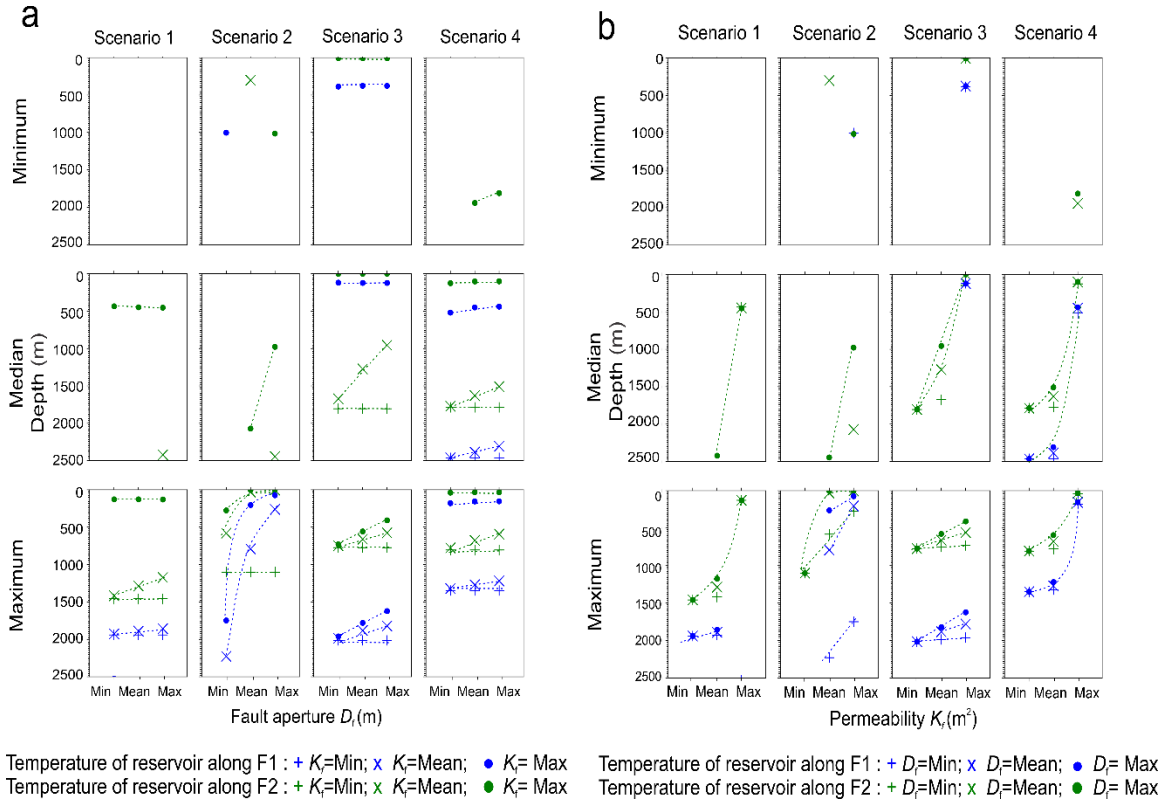448 underlying the Nevado del Ruiz volcanic complex of Colombia, where hot springs are

29

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).

Figure 14 caption:

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

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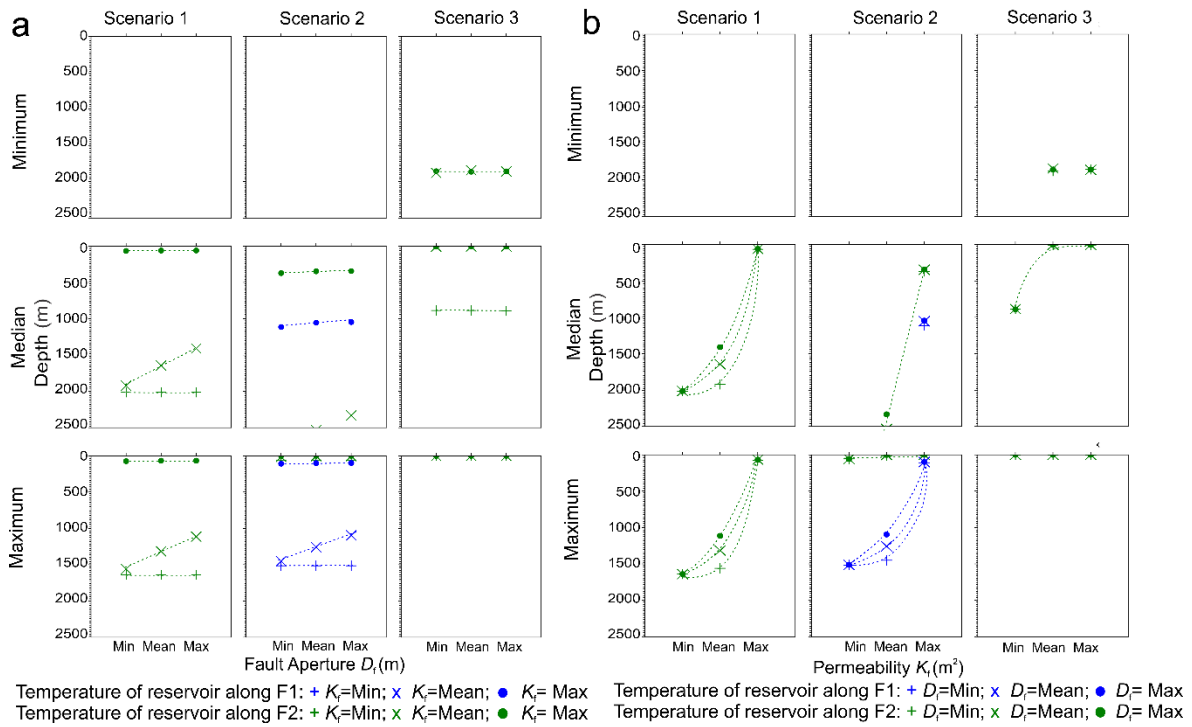

485

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 ~120 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 ~100 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 ($k_f > 10^{-14}$ 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 ($D_f > 250$ μm) 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 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 Mw > 5 in the study areas; (Bertil and Regnoult 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° 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 °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**

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1   **Understanding heat transfer along extensional faults: the case <mark>of the</mark> Ambilobe and**

2   **Ambanja geothermal systems <mark>of</mark> Madagascar**

3

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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 $>10^{-14}\,\mathrm{m}^2$. 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 $\mathrm{mWm^{-2}}$ 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} m^2, 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.

2. Geological setting and geothermal context

2.1 Tectonic framework and regional fault system

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

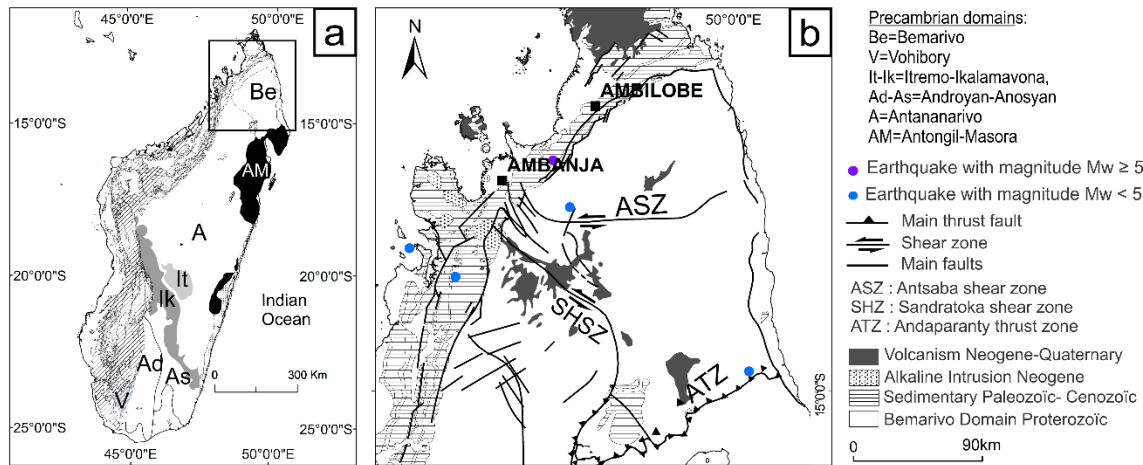137 Montagne d'Ambre, in the extreme north of Madagascar (Chorowicz et al. 1997)

138

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).
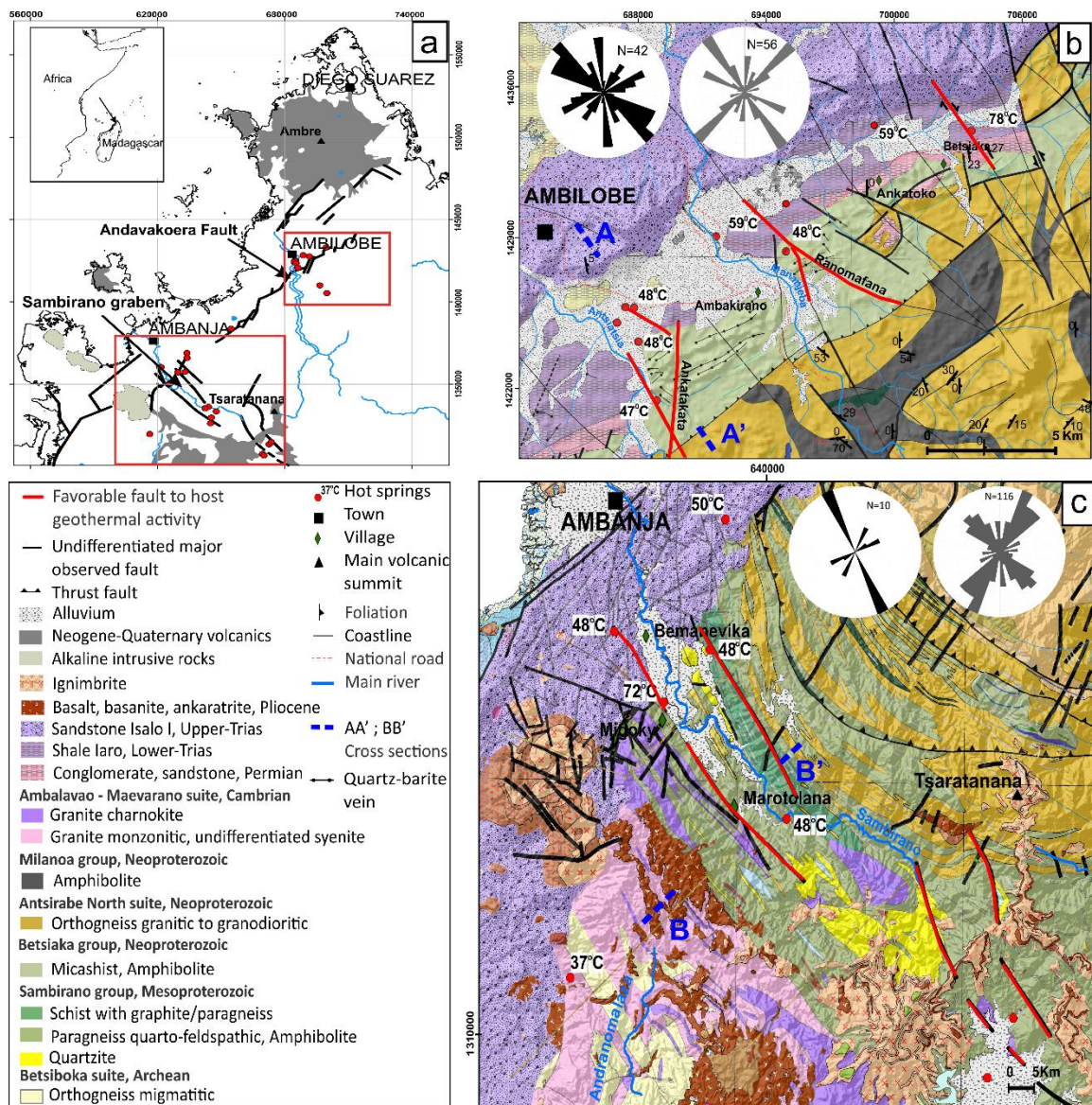
169

Figure 2 (a) Location of the Ambilobe and Ambanja geothermal areas. (b) and (c) Detailed geology of each area (modified from Roig et al. 2012). The rose diagrams illustrate the major fracture trends (in black) established from field data collected in 2018 and the major faults trends (in grey) established from the map data of Roig et al. (2012).
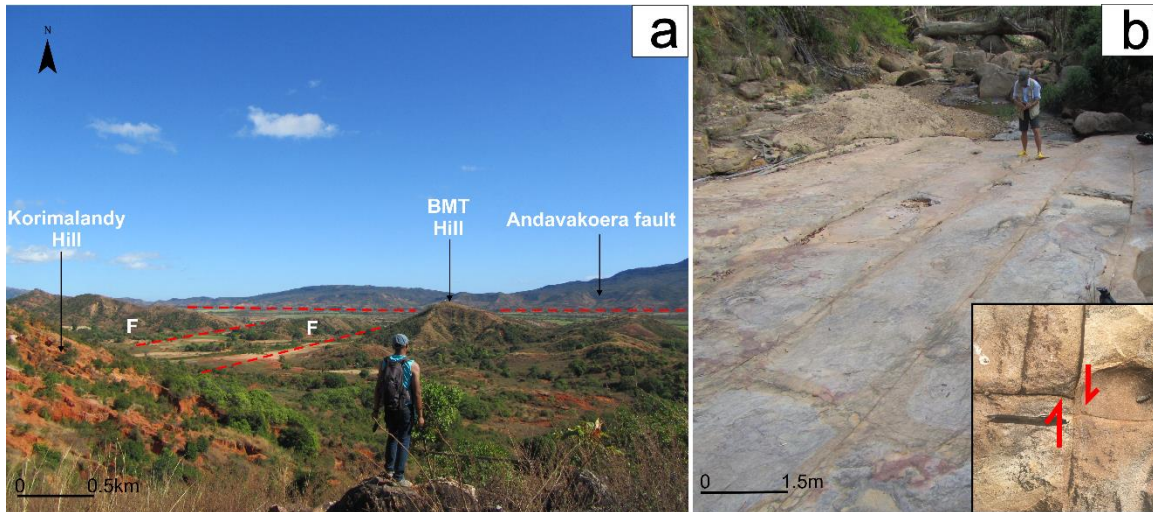
174

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

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

Using chemical geothermometers (Gunnlaugsson et al. 1981) and the Giggenbah diagram (Figure 4), the reservoir temperatures in the Ambilobe and Ambanja areas are expected to be 140 and 200 °C, respectively.
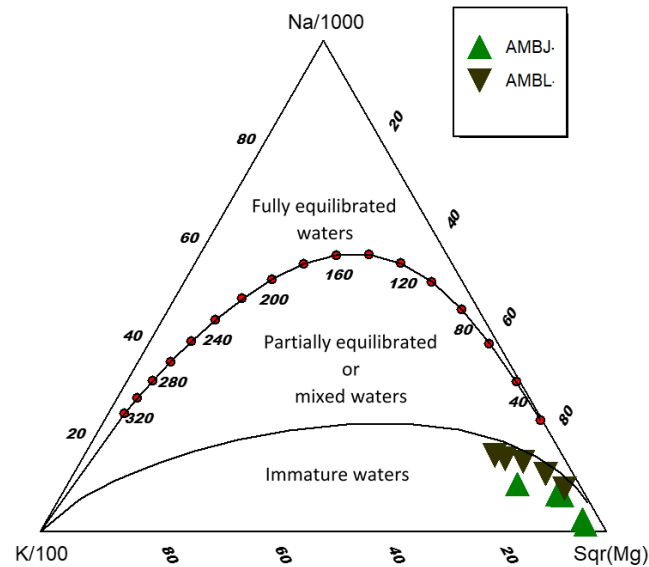
Figure 4: Chemical composition of waters from the Ambilobe (AMBL) and Ambanja (AMBJ) hot springs plotted on a ternary Na-K-Mg diagram (Giggenbach 1988). The Na, K, Mg concentrations were reported in Gunnlaugsson et al. (1981).

2.3 Lithosphere structure and geological formations

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

The geological formations of the Ambilobe and Ambanja areas and their thermo-hydraulic properties have been described in Rajaobelison et al. (2020); and Rajaobelison et al. (2021). The Permo-Triassic sedimentary rocks of the Ambilobe Basin, overlying the Proterozoic 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.
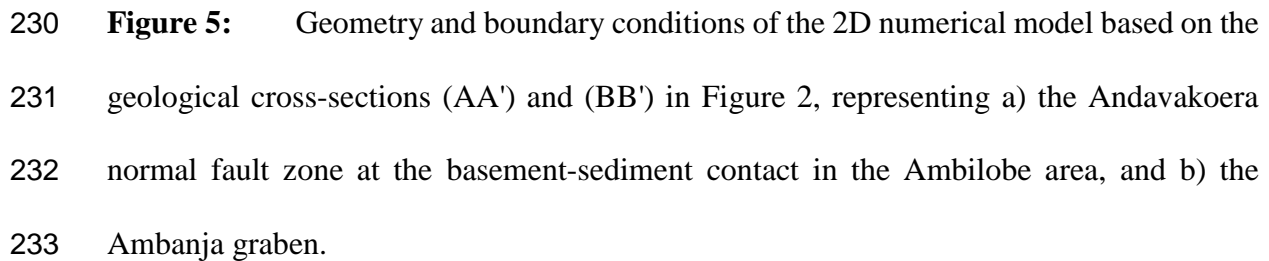
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Figure 5: Geometry and boundary conditions of the 2D numerical model based on the geological cross-sections (AA') and (BB') in Figure 2, representing a) the Andavakoera normal fault zone at the basement-sediment contact in the Ambilobe area, and b) the Ambanja graben.

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Table 1   Fault scenarios

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

248   where λ_b (Wm^{-1}K^{-1}) is the bulk thermal conductivity; T (°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 (J kg^{-1} 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 $\varnothing$

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					Ambanja			
Formation	Sediments			Basement		Basement			
Geological Units	Permian Sandstone	Eo Triassic shale	Triassic sandstone	Mica Shist Amphibolite	Ortho-gneiss	Syenite	Para-gneiss		
Mean $\varnothing$	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}	$1.0\ 10^{-15}$	m²	Rajaobelison et al. (2021)
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}	
Mean A (LC)	0.72								Horton et al. (2016)
A- Total Crust	1.2							10^{-6} W m^{-3}	
Fault Properties	F1; F2								
Aperture	Min.		Mean			Max.			
D_f	250×10^{-6}		1.1×10^{-3}			2×10^{-3}		m	Current study
Permeability k_f	10^{-14}		10^{-10}			10^{-7}		m²	

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

272 Transient thermal conductivity λ (Wm^{-1} K^{-1}) and diffusivity α (m^2 s^{-1}) were measured with

273 the optical scanning method using an infrared scanner developed by LGM Lippmann. The

274 heat capacity, c (J kg^{-1}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).

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. Bisdom 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)

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.
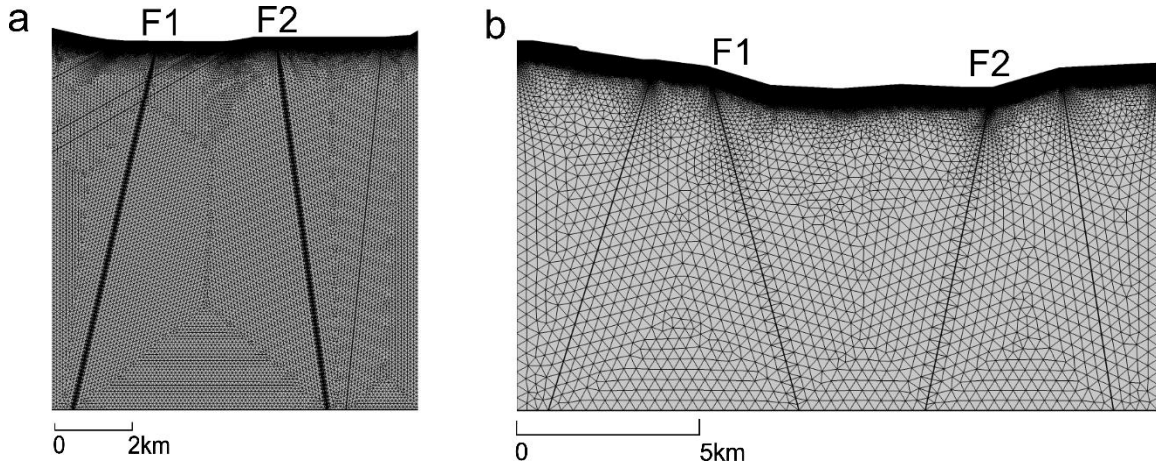
a F1 F2
0 2km

b F1 F2
0 5km

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

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

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

where N is the sample number, ΔT_i is the temperature variation at depth $x_i=(i-1)D/N-1$ along the chosen cutline where the mesh size of the model is refined. Here, D is the depth of the model. It demonstrated that a stable solution was obtained above 10^4 elements with a difference of about 1 °C or less (Figure 7).
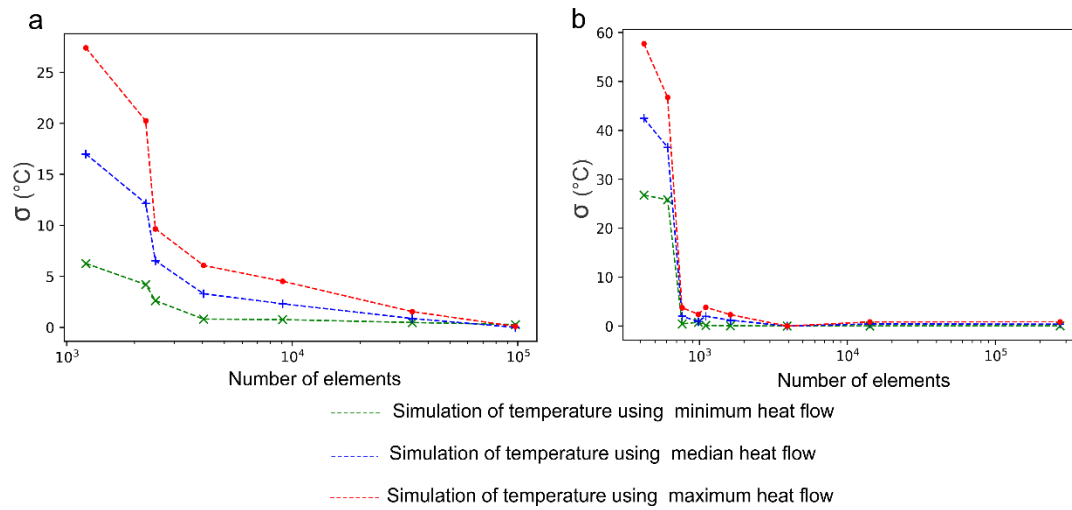
Figure 7: Mesh convergence study for the a) Ambilobe and b) Ambanja models.

3.5 Boundary conditions

3.5.1 Groundwater flow conditions

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

3.5.2 Heat transfer conditions

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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 (Ts) and altitude (z):

322 $$T\text{s} = -0.0046z + 26.85 \tag{3}$$

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 $$Q_{cpd} = \lambda \frac{T_{CPD} - T_0}{Z_{CPD}} - A \frac{Z_{CPD}}{2} \tag{4}$$

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 1.5×10^{-6} W m^{-3} and 0.72×10^{-6} W m^{-3}, respectively (Table 2; Horton et al. 2016).

336 λ (W m^{-1} 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 $$Q_{10} = Q_{cpd} + A_{LC}\,H_{LC} + A_{UC}\,(H_{UC} - H_{model})$$ (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	$T_s=-0.0046z+26.85$			°C
Heat flow at base (Q_{10})	Min	Mean	Max	mWm^{-2}
	50	99	148	

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.

353

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).
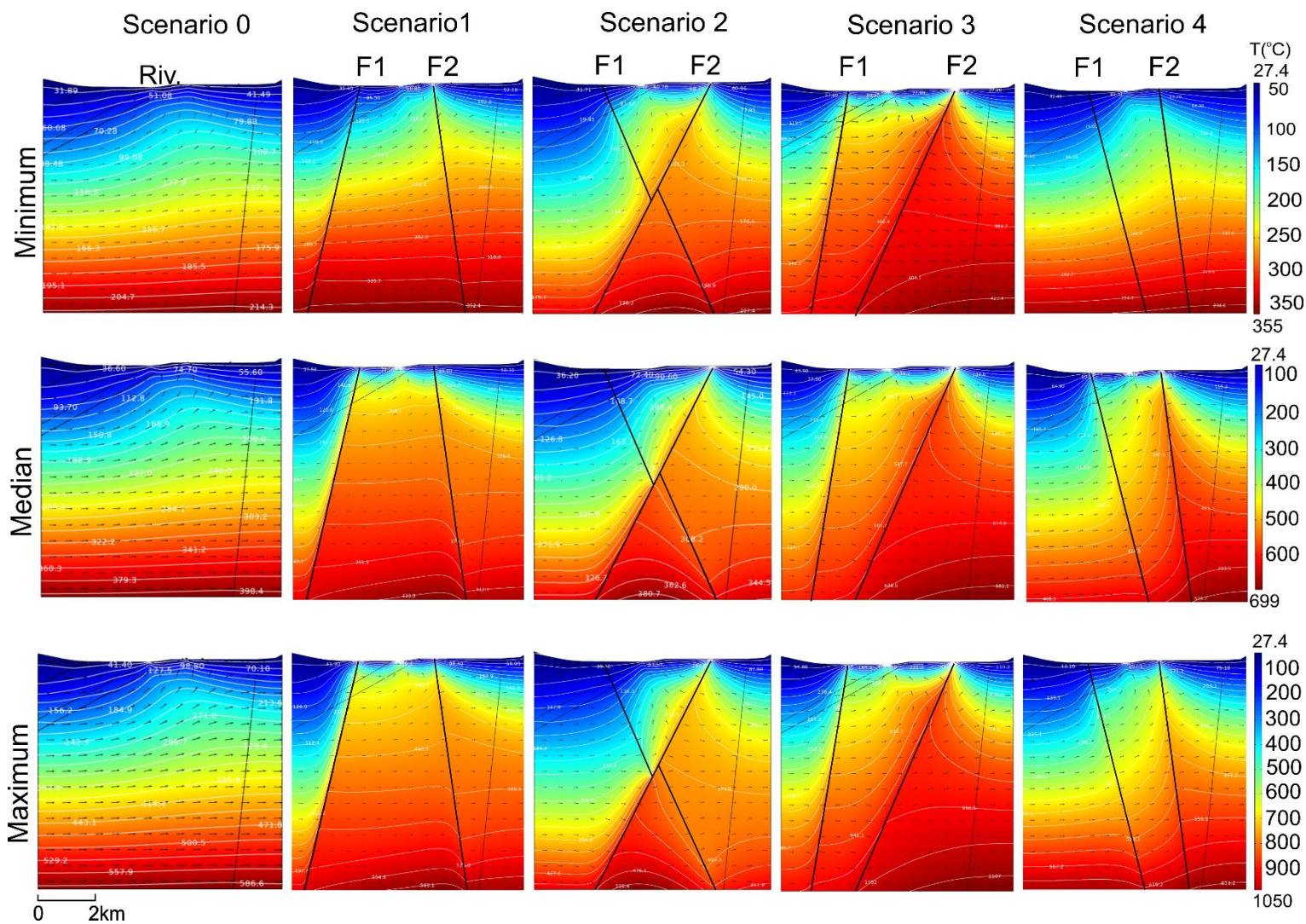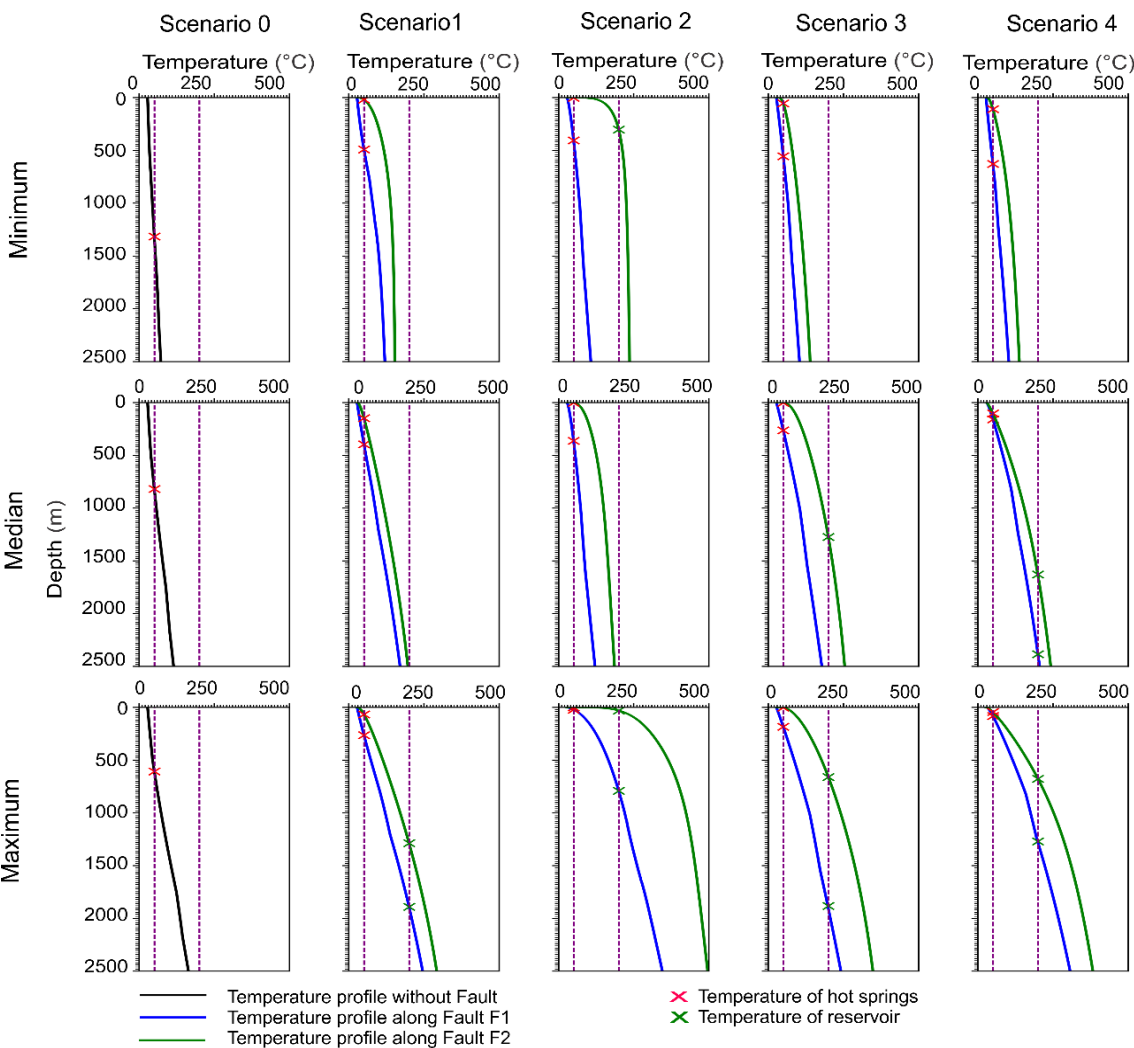
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371

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
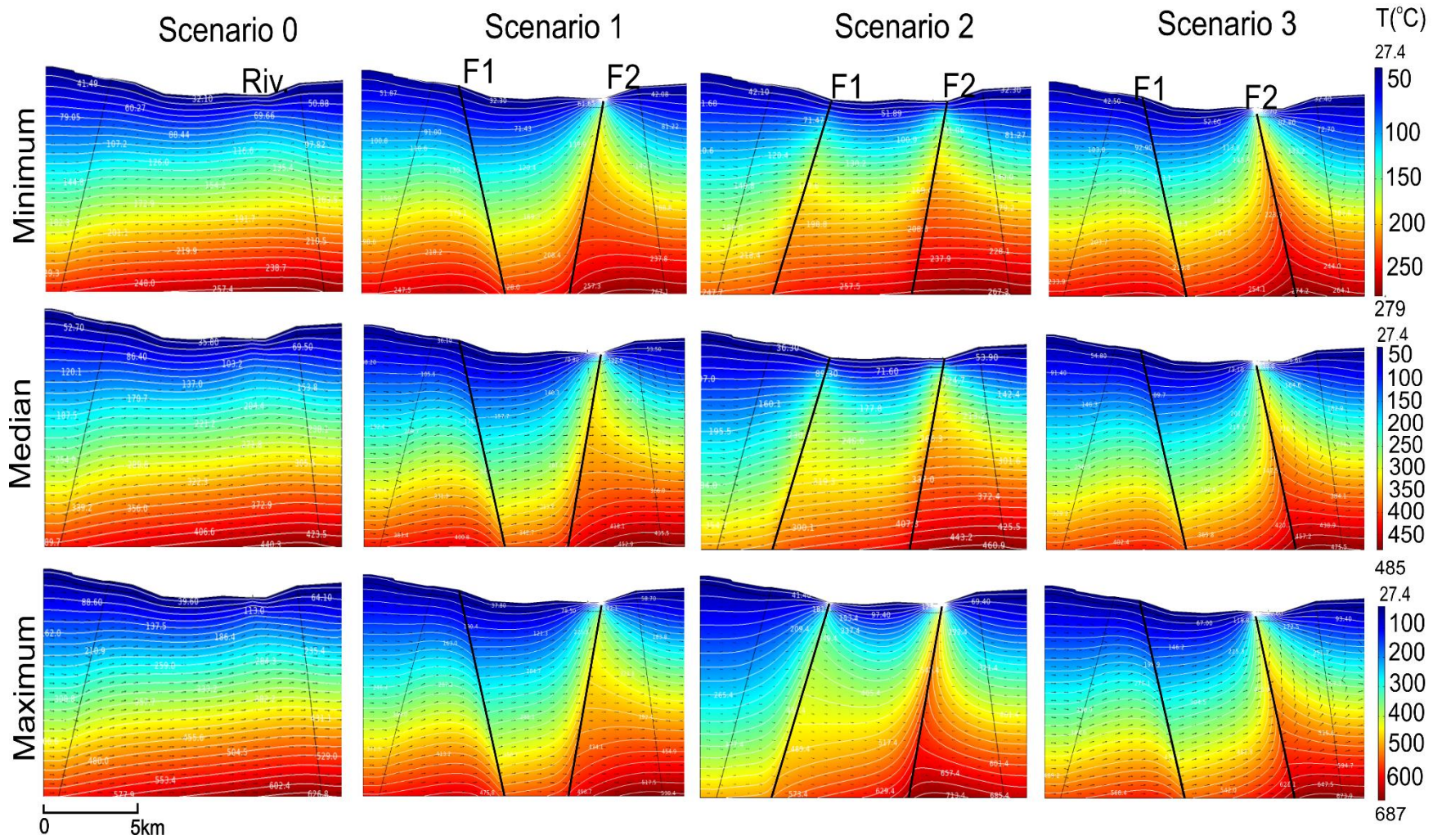
379   fault-free model.

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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.
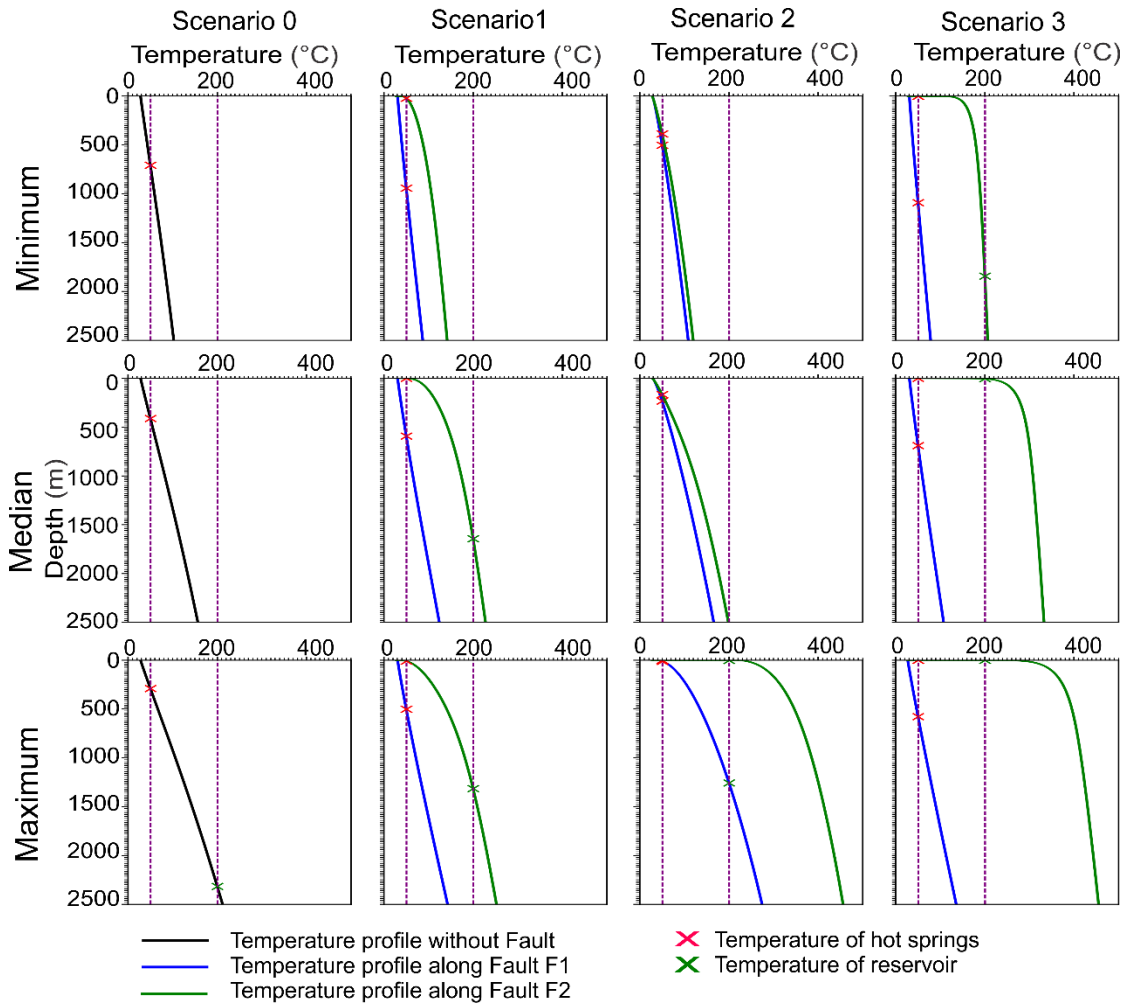
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Figure 11   Temperature profiles as a function of depth along fault lines for the Ambanja

2D model. The temperature profiles in scenario 0 were obtained from an average cutline

drawn in the fault-free model.

The magnitude of the Darcy velocity varies between 10^{-9} and 10^{-2} m s^{-1} along the faults

(e.g. Figure 12). The simulated outflow velocity at the upper-ends of favorable faults

(Table 6 and Figure 12) shows no difference or a 1-2 magnitude difference compared to

the measured flow velocity at some hot springs, which varies between 10^{-9} and 10^{-7} m s^{-1}

(Table 6; Gunnlaugsson et al. 1981).

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

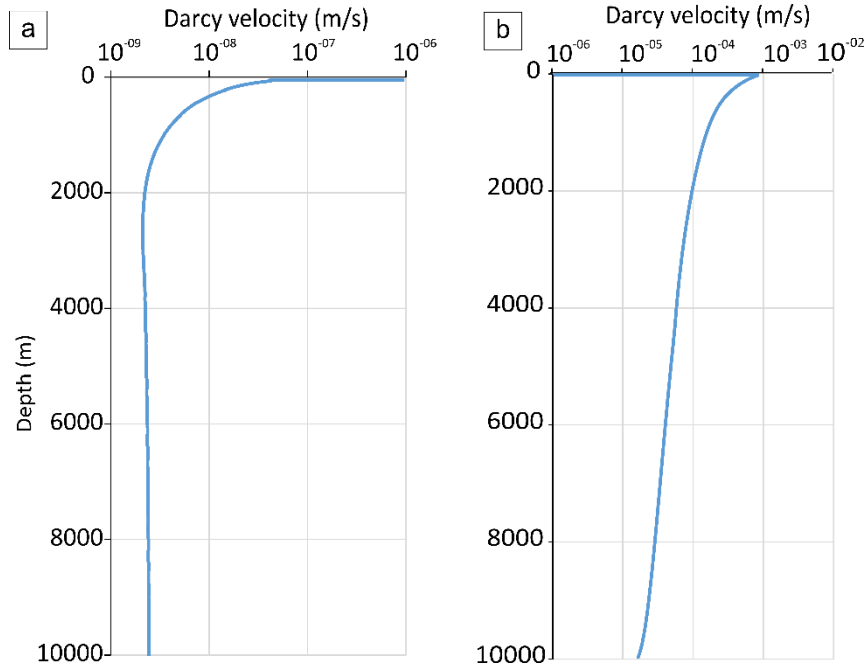|	Ambilobe				Ambanja	
Most realistic scenario	1	2	3 and 4	3 and 4	1	1
Heat flow Q_{10} (mWm^{-2})	Max	Max	Median	Max	Median	Max
Favorable fault	F2	F1	F2	F2	F2	F2
Fault dip	85° SE	60° NW	75° SE and 85° NW	75° SE and 85° NW	80° NE	80° NE
Measured flow at hot springs, (m s^{-1}) (Gunnlaugsson et al. 1981)	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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Figure 12   a) Ambilobe 2D model, scenario 3: flow velocity along fault F2, maximum

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

heat flow value. Results for F1 and F2 use mean aperture and permeability values.
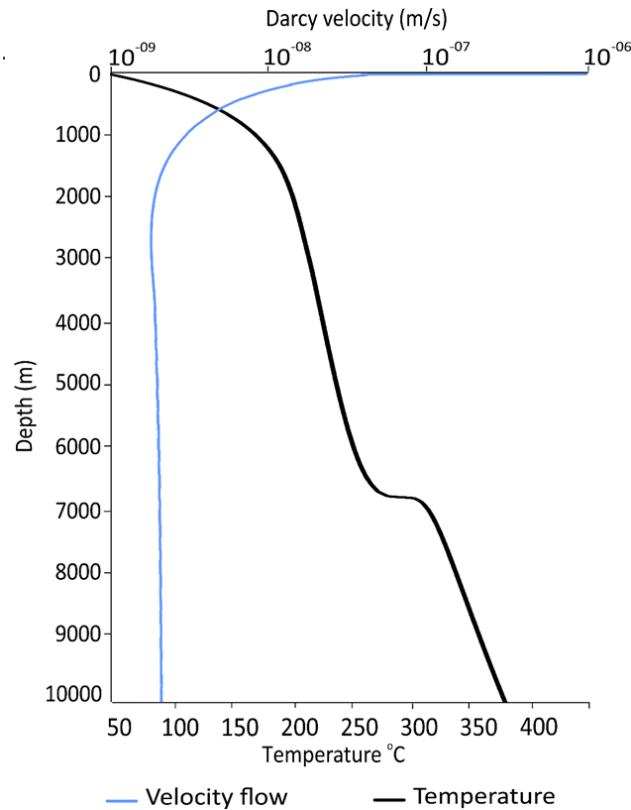
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Figure 13   Variation of simulated flow velocity and temperature as a function of depth along the fault. Ambilobe 2D model, scenario 3, fault F2 and median heat flow value.

4.2 Influence of faults

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 $< 90°$ 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

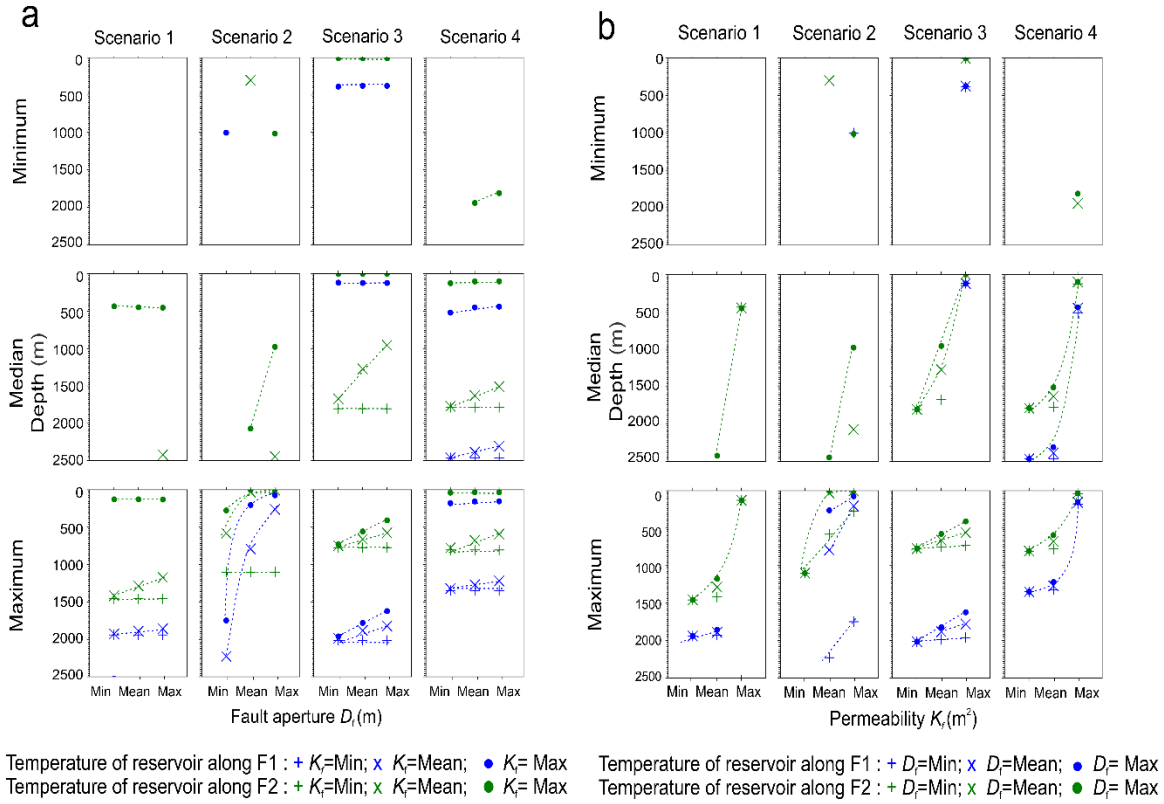448 underlying the Nevado del Ruiz volcanic complex of Colombia, where hot springs are

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

31

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.
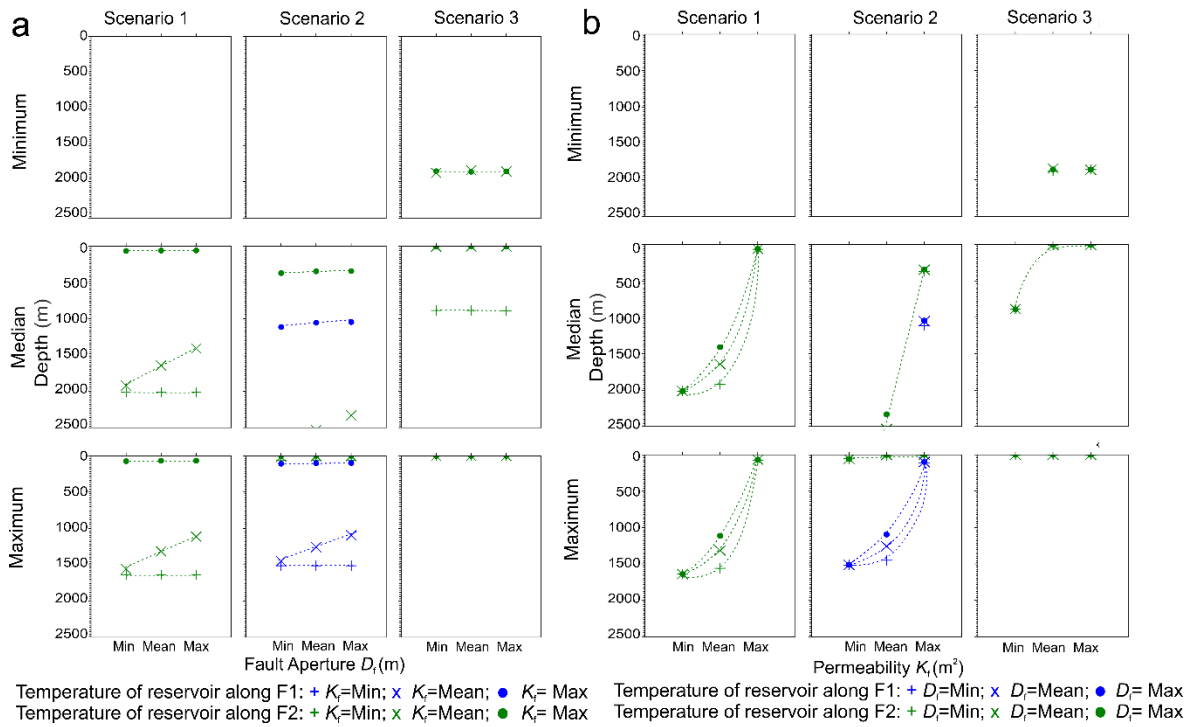

485

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

32

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 ~120 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 ~100 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 ($k_f > 10^{-14}$ 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   ($D_f > 250$ μm) 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 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 Mw > 5 in the study areas; (Bertil and Regnoult 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

36

582   should be normal faults with < 90° 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 °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.

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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.