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Crustal Fault Zones as underexploited geothermal resources: Contribution of numerical modelling and comparison with natural systems

Hugo Duwiquet[1,2,3*], Laurent Guillou-Frottier[1,2], Laurent Arbaret[2], Fabien Magri[4,5], Theophile Guillon[1], Mathieu Bellanger[3], Simon Lopez[1], Emmy Penhoët[6] and Michael J. Heap[7,8]

[1]BRGM, 3 av. C. Guillemin, BP 36009, Orléans Cedex 2 F-45060, France. [2]Univ. Orléans, CNRS, BRGM, ISTO, UMR7327 F-45071 Orléans, France. [3]TLS-Geothermics, 91 chemin de Gabardie, 31200, Toulouse, France. [4] Division Research/International, BASE, The Federal Office for the Safety of Nuclear Waste Management, Berlin, Germany. [5] Institut of Geological Sciences, Hydrogeology Group, Freie Universität Berlin, Berlin, Germany. [6] Georessources Et Environnement, ENSEGID-Bordeaux INP, Avenue Des Facultés, 33400, Talence, France. [7]Univ. de Strasbourg, CNRS, ITES, UMR 7063, 5 rue René Descartes, Strasbourg F-67084, France. [8]IUF, France

*hugo.duwiquet@gmail.com

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ABSTRACT

The exploration and discovery of new targets for geothermal power generation could help to reach environmental and energy policy objectives. Crustal Fault Zones (CFZ) are interesting geological targets for high-temperature geothermal resources in naturally fractured and deep basement zones. Field and laboratory studies have already shown the ability of these systems to favor fluid flow down to the brittle-ductile-transition. However, several key questions about exploration still exist, in particular the role of their structural dip, their permeability, and the effect of mechanical stress and more broadly the fundamental role of tectonic regimes on fluid flow in naturally fractured basement domains. Considering 2D and 3D numerical modelling, with thermal-hydraulic (TH) and thermal-hydraulic-mechanical (THM) couplings, two trends can be identified and integrated for the exploration of these targets (i) vertical faults concentrate the highest temperature anomalies at the shallowest depths (ii) strike-slip systems favor the largest temperature anomalies when compared to compressive or extensive systems. From these results it also appears that the presence of an external heat source (i.e. magma chamber or crustal thinning) is not a necessary condition for the formation of a temperature anomaly.

Geological and geophysical data suggest that the Pontgibaud fault zone (French Massif Central) is a CFZ that hosts an active hydrothermal system at a depth of a few kilometers. We conducted an integrated study to assess its high temperature geothermal potential. Field measurements are used to constrain the 3D geometry of the geological structures. 2D (thin-section) and 3D (X-ray microtomography) observations point to a well-defined spatial propagation of fractures and voids, exhibiting the same fracture architecture at different scales (2.5 µm to 2 mm). Moreover, measurements of porosity and permeability confirm that the highly fractured and altered samples are characterized by high permeability values, with one sample characterized by a permeability as high as 10^{-12} m^2. Finally, a large-scale 3D numerical model of the Pontgibaud CFZ, based on THM coupling and the comparison with field data (temperature, heat flux, and electrical resistivity), allowed us to explore the spatial extent of the 150°C isotherm, which reaches a depth of 2.3 km. Although based on simplified hypotheses, our model reproduces field data. A multi-disciplinary integrative approach based on coupled 3D modelling proved to be an efficient way to assess the geothermal potential of CFZ and predict temperature distributions. Consequently, it can also be used as a predictive tool to develop high-temperature geothermal operations within basement rocks hosting large-scale fault systems.

1. INTRODUCTION

By 2050, geothermal energy could account for 3.5% of the world's electricity production (Geothermal Energy Association. Annual U.S. & global geothermal power production report, 2015). Exploring new targets for high-temperature geothermal energy could either achieve or exceed these objectives.

Geothermal exploration, as well as the targeting of potential reservoirs, depend on a general understanding of the geological and physical factors that may influence the presence of such reservoirs. Previous studies have noted that a geothermal resource requires the presence of a heat source, a fluid, and sufficient permeability to allow the fluids to flow. These three parameters make the exploration of such reservoirs constrained to particular geodynamic contexts, such as magmatic arcs, subduction zones, pull-apart basins, or extensional and crustal thinning systems (Moeck, 2014, Jolie et al. 2021). However, in basement domains, faults and fractures can create localized anomalous high permeability zones (Gleeson and Ingebritsen, 2016). Buffon (1778) has documented the fact that fluids can circulate in these fractured and naturally permeable media. Within these naturally permeable zones, vertical thermal instabilities exist and are associated with convection cells (Lowel, 1975; Murphy, 1979; López and Smith 1995; Faulds et al. 2010; Magri et al. 2016).

This mode of heat transfer by matter movement causes the formation of positive and negative temperature anomalies in these anomalous permeable zones. Different parameters influence the presence of this kind of convective regime, such as fluid properties (viscosity and density). Among these parameters, Turcotte and Schubert (1982) looked at the thermal conditions necessary for convection to take place in a porous medium. These authors have shown that, with a geothermal gradient greater than 20°C/km, the convection heat transfer mode occurs over length scales greater than several kilometers when permeability values are greater than 10^{-15} m^2. Otherwise, for this permeability condition, and for a geothermal gradient below 20°C, the heat transfer is achieved by conduction. The European continental crust has an average geothermal gradient of 30°C/km. Overall, in Europe, the thermal conditions are more than sufficient to allow fluids to circulate by convection. Under these thermal conditions, it appears that the presence of an external heat source (presence of a magma chamber and/or crustal thinning context) would no longer be a *sine qua non* condition for a geothermal power system in zones where the permeability is greater than 10^{-15} m^2. If on a country or regional scale it is usual to target abnormally hot zones for high-temperature geothermal energy, it could then be possible to target abnormally permeable zones within the Earth's crust. If this potential is proven, it could considerably increase the number of targets for geothermal power plants. This study focuses on zones, not abnormally hot, but abnormally permeable within the continental crust, susceptible to host high-temperature geothermal reservoirs.

In the crustal domain, it appears that Crustal Fault Zones (CFZs) are large, deep, localized deformation zones (Ben-Zion and Rovelli, 2014). These zones modify the properties of the crust above the brittle-ductile transition (BDT). This results in interconnected and interlocking structures (Faulkner et al. 2010). Field observations show lateral facies variations between damaged, crystallized and undeformed zones. This leads to a significant variation of the permeability within these deformation zones (Faulkner et al. 2003). Understanding the distribution of permeability in the crust remains an essential component for the general comprehension of a geothermal model in the crustal domain, and therefore for the success of geothermal prospect (Moeck, 2014). Previous studies have highlighted some other parameters that influence fluid flow in a fractured system in a basement domain. For example, considering a vertical fault zone, and depending on the permeability ratio between the fault and the basement, López and Smith (1995) have highlighted different modes of heat transfer. However, in natural fracture systems, the dip, which describes the plane orientation with respect to horizontal can vary from low angle to up to 90°. Thus, in addition to the permeability ratio between the fault and the basement, we will consider the dip of the structure as a variable parameter impacting the fluid flow and the heat transfer mode. Also, tectonic deformation has been considered as a driving force that influences fluid flow in different geological contexts (Ord and Oliver, 1997b). Thus, one could assume that the stress orientation and stress intensity could also have an influence on the fluid circulation in the three dimensions of space. If this trend is confirmed, it could allow us to consider the orientation of tectonic stresses as a parameter impacting fluid circulation within a large faulted zone.

The present study aims to understand the potential of a new and novel types of geothermal play system for high temperature and electricity production: CFZs. The main goal of this study is therefore to understand hydrothermal fluid dynamics in CFZs. The correlation between field studies, petrophysical data and numerical modelling should improve the geothermal exploration phase of CFZs. This work aims to determine how the hydrothermal systems associated with CFZs are organized, and what are the controlling factors.

This study synthesizes work completed as part of a thesis started in 2019. This thesis was established in collaboration with the French Geological Survey (BRGM), the Orleans Institute of Earth Sciences (ISTO, in France) and TLS Geothermics, a French geothermal exploration company. These results have been the subject of some publications (Duwiquet et al. 2019a; 2019b; Guillou-Frottier et al. 2020; Duwiquet et al. 2020a; 2020b; Duwiquet et al. 2021a; 2021b; Duwiquet et al. submitted). The methods, results and discussion are detailed in the thesis manuscript Duwiquet, 2022 (open access). More broadly, the topic of this thesis is part of the ANR GERESFAULT project (ANR-19-CE05-0043), which proposes to explore the geothermal potential of CFZs with a combination of field studies, experimental data, geophysical and numerical modelling (9 public and industrial partners).

2. SOME ELEMENTS TO FACILITATE THE EXPLORATION OF THE CFZ

In order to quantify the effect of unconstrained parameters on fluid flow and its consequences on temperature anomalies a series of numerical simulations using Comsol Multiphysics™ software have been performed. The first step was to make a benchmark of the numerical tools in order to reproduce the data already published by Magri et al. (2017) and Guillou-Frottier et al. (2020). The results and details of this benchmark are presented in Duwiquet et al. (2021b) and Duwiquet (2022). Thus, considering simplified geometries, but realistic physical properties we present different parametric studies. We successively tested the effects of geological dip, permeability ratio, stress intensity and direction, and then tectonic regimes on fluid flow. We investigated the consequences of these parameters on the intensity and depth of temperature anomalies. These parametric studies were performed in 2D and 3D. Considering different couplings, we used Darcy's law, Fourrier's law and Hooke's law in our different numerical experiments. The model setup, details on the couplings and the equations used are also presented in Duwiquet et al. (2019); Guillou-Frottier et al. (2020); Duwiquet et al. (2021); Duwiquet, (2022). The permeability imposed on numerical model follow the permeability variation conceptually described and applied to the Carboneras fault zone (Andalusia, Spain) system (Faulkner et al. 2003). This permeability variation is detailed and described in section 3. This representation of the permeability variation is also consistent with our field data (see section 3) and will be integrated in our large-scale numerical modelling.

2.1 Dip and permeability effects of CFZ on fluid flow

To investigate the dip geological structures effect on the heat transfer mode, we have considered the dip as a variable parameter. The permeability ratio between the fault and the basement rock was also taken into account. This first parametric study has allowed us to highlight areas to be favored for the exploration of these new potential targets. The results of this study are summarized in Figure 1.

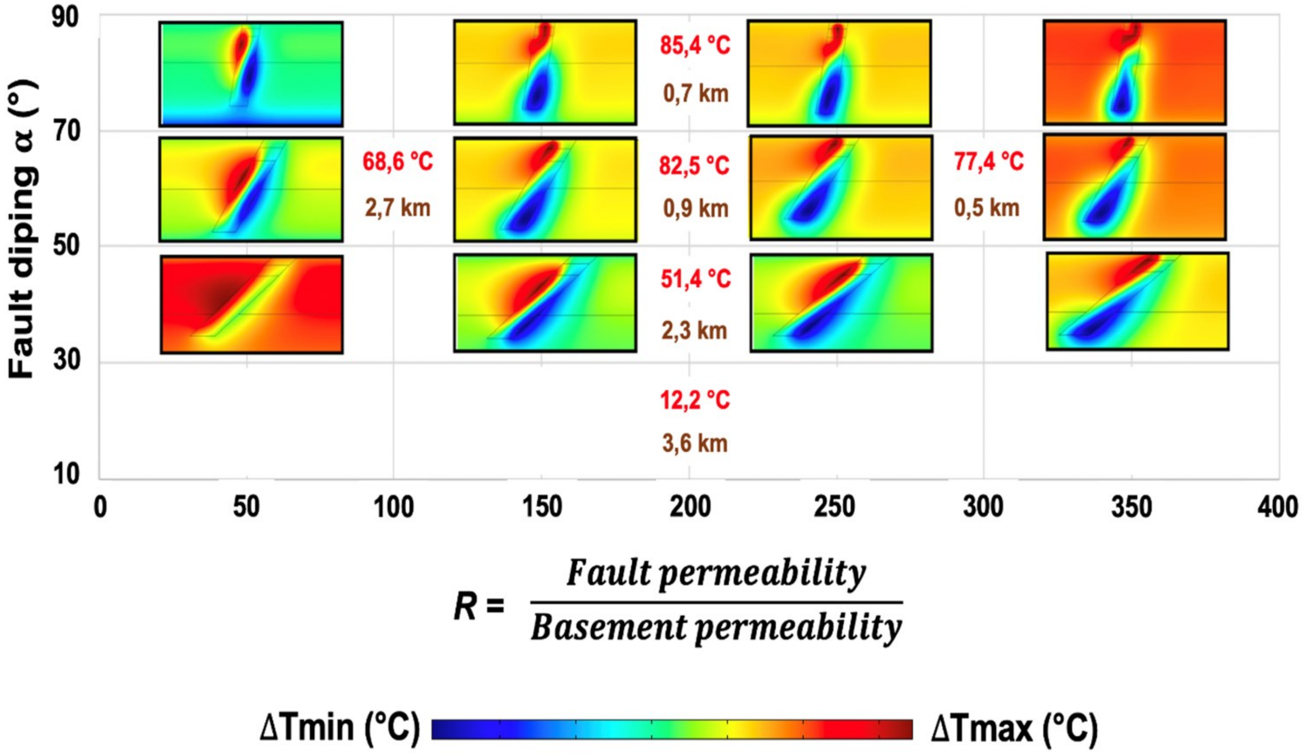

Figure 1 : Results of numerical experiments (n=216). Heat transfer as a function of fault dip and permeability ratio between fault and the basement (n=216). Positive temperature anomaly values are shown in red and their depth in brown. Between 10 and 30°, the visible absence of negative temperature anomalies is related to the normalization of the temperature scale. In 2D with a TH coupling, it appears that vertical structures concentrate the most intense temperature anomalies at the shallowest depths. Boundary conditions, meshes, physical properties are given in Duwiquet et al. 2019; Duwiquet 2022. However 3D effects could modify these conditions.

More than 200 simulations were performed. The images in Figure 1 represent temperature anomalies (ΔT), corresponding to abnormally hot and abnormally cold temperatures compared to an undisturbed (conductive) thermal regime. As it can be seen in Figure 1, for R = 200, as the dip of the fault zone increases from 10 to 90°, the temperature values increase from 12 to 85.4 °C (red numbers). Thus, for a fixed R ratio, the highest thermal anomaly will be for a vertical fault zone. The depth of the thermal anomaly also varies as a function of fault dip. By increasing the fault dip from 10 to 90°, the depth of the thermal anomaly (brown numbers) decreases from 3.6 to 0.7 km. Thus, for a fixed R value, vertical structures will result in the largest thermal anomalies at the shallowest depths.

By observing the variations in the temperature anomalies, we can see that when R increases for a fixed angle of 60°, the values of the thermal anomalies are 68.6, 82.5 and 77.4°C. Indeed, an increase in the R ratio does not show a significant increase in the temperature anomaly. However, the depth of these same anomalies decreases from 2.7 to 0.5 km. So, for a fixed dip, when R ratio is high, the thermal anomaly is higher at a shallower depth. Therefore, a fault zone with a high dip and a high R ratio will result in the largest thermal anomalies at the shallowest depths. The driving force controlling these fluid circulations is the buoyancy force. Here, the convection is free (which will not be the case when we integrate a mechanical parameter, see part 2.2.2).

However, the fluid circulation can take place in three dimensions (Magri et al. 2016; Patterson et al. 2018). The trends obtained in 2D could therefore be modified.

In 3D, with a TH coupling, Guillou-Frottier et al. (2020) tested the influence of the dip of a structure for a fixed permeability. Four experiments were performed, varying the angle of the permeable structure from 0 to 45°. Figure 2 represents the results of these experiments. It appears that differences in terms of temperature anomaly values exist. The largest temperature anomaly is obtained in the vertical case. The trends obtained in 2D appear to be confirmed in 3D. Whether in 2D or 3D, the origin of this control could be the temperature difference between the base and the top of the geological structure. Considering a constant structure length, the temperatures at the base are higher at high dips than at low dips. This difference between the base and the top of the permeable structure has a direct influence on the formation of convection cells. Physically characterizing the convection cells, the Rayleigh number considers the temperature difference between the upper and lower boundary of the system considered. Therefore, by fixing the permeability, a large temperature difference between the upper and lower boundary of faulted system may favor the formation of convection cells. However, other parameters could change the way fluids can flow, and thus affect the thermal distribution of the naturally fractured and permeable media. Among these parameters, tectonic deformation has been considered as driving force that influence fluid flow in different geological contexts (Ord and Oliver, 1997b).

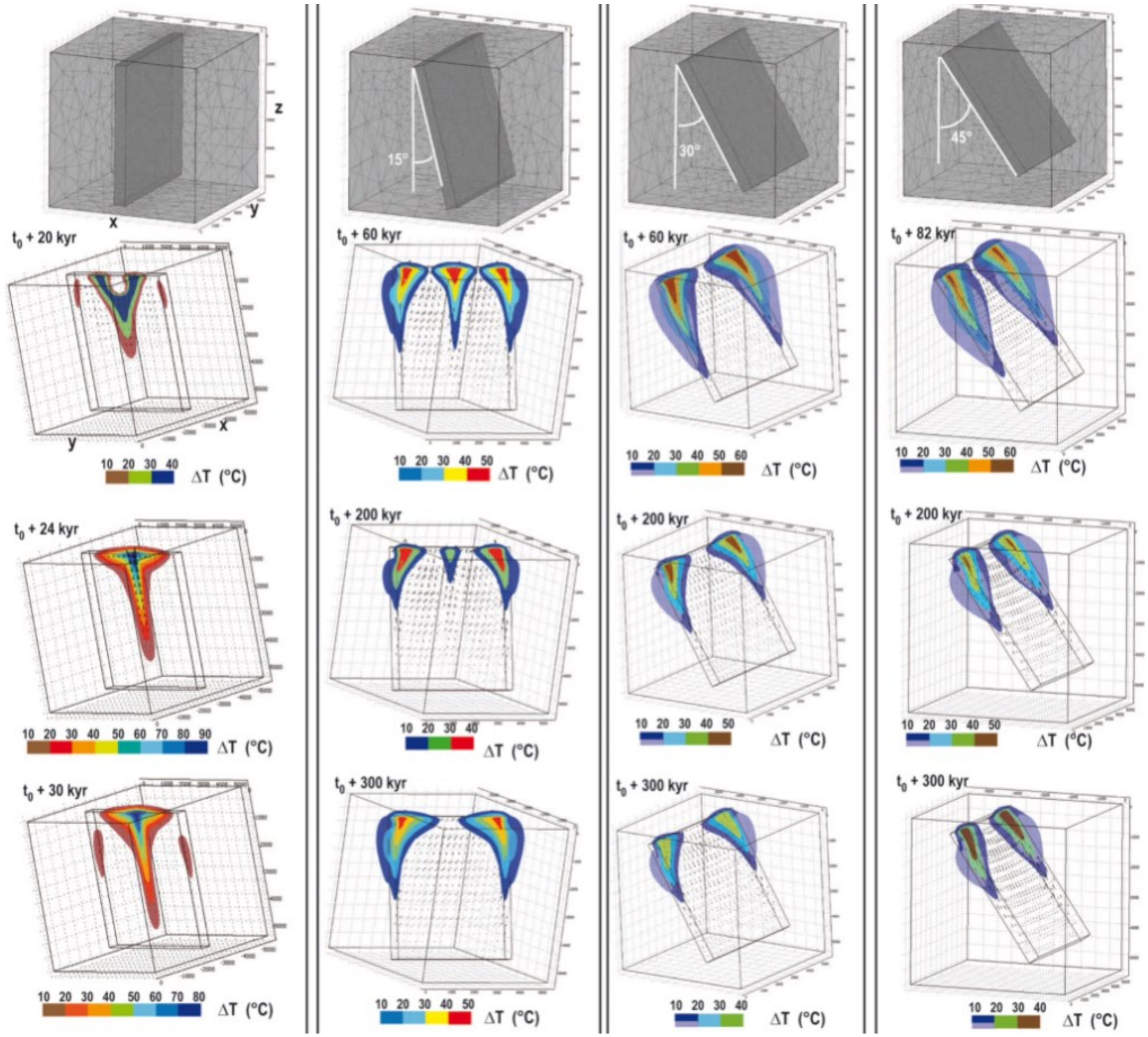

Figure 2 : Representation of four experiments from Guillou-Frottier et al. (2020). The largest temperature anomaly are obtained in the vertical case. This confirms the trends observed in 2D, and seems to favor that in the exploratory phase, targeting vertical deformation zones could be favorable for geothermal reservoirs.

2.2 Some mechanical effect on fluid flow within CZF

2.2.1 Stress direction, stress intensity effects on fluid flow within CFZ

We assume that the stress orientation and stress intensity could also have an influence on the fluid circulation in 3D. If this trend is confirmed, it will allow, in the exploratory phase, to consider the orientation of tectonic stresses as a parameter that impacts fluid circulation within a fracture zone. To account for the mechanical aspect, we have performed a preliminary 3D THM model in which the hypotheses are simple with the aim to focus on one single but important issue: could mechanical stresses affect the hydrothermal convective regimes? To our knowledge, THM models are generally applied to purely pressure-driven flow, where fluid density is constant and thus with no buoyancy-driven components (see however Wang et al. 2019; Shi et al. 2019). However, Vallier et al. (2020), used a similar approach as ours but with another objective—the study of mechanical effects on gravity anomalies—and so no information on the coupling between fluid flow and mechanical effects could be retrieved from these results. Thus, based on a poroelastic assumption, we explored the effect of stress intensity, stress direction on fluid flow and temperature anomalies using numerical modelling. The numerical setup is detailed in Duwiquet et al. (2021); Duwiquet (2022).

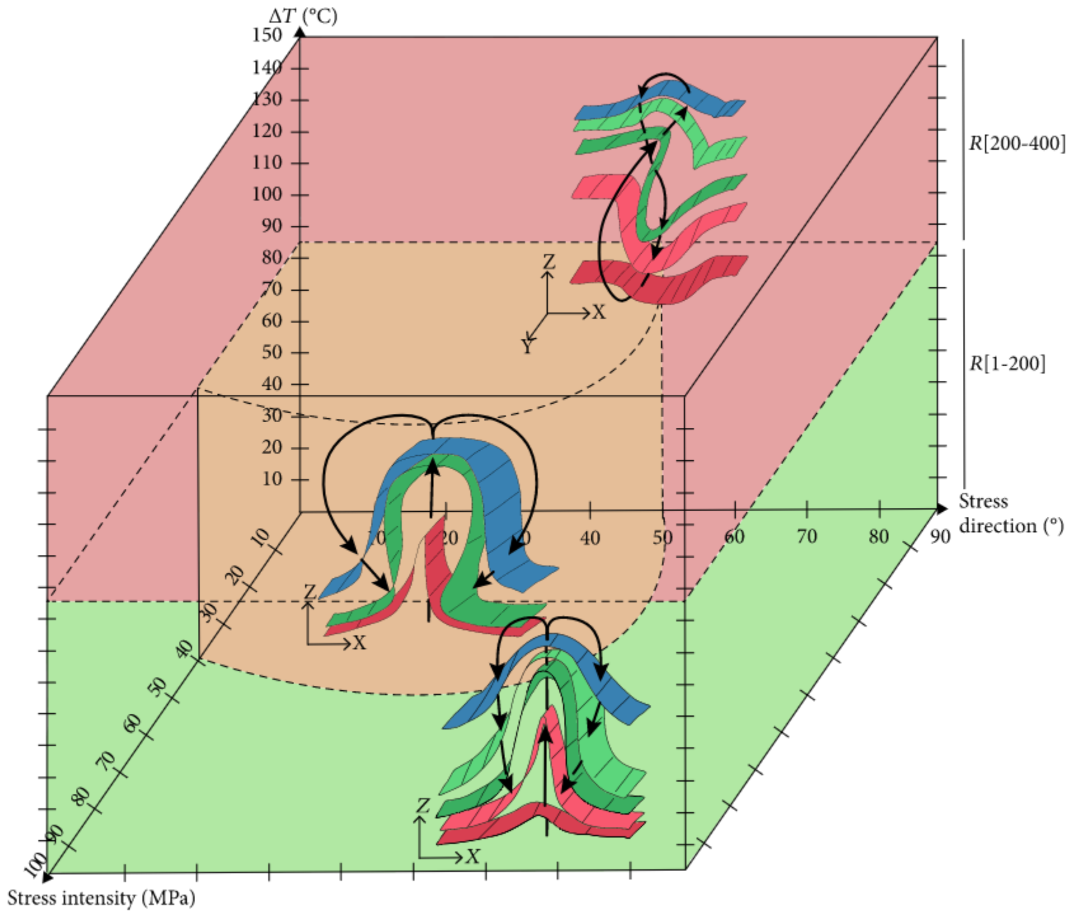

Figure 3 : Fluid circulation and isotherm deformation in a fractured hydrothermal system as a function of 3 parameters: permeability ratio, direction and stress intensity. In the brown area are the blob-like convection patterns. In the green zone are the finger-like convection patterns. In the red zone are the double-like convection patterns (see details in the text). The volume covered by the temperature anomaly is greater in blob-like than in finger-like. It seems important to dissociate these different convective regimes.

More than 2,500 numerical simulations were run to understand the combined effects of a major horizontal stress (both in direction and magnitude) and fault permeability on the intensity and depth of the positive temperature anomaly along a vertical fault. Observations of the convective patterns from the numerical simulations make it possible to distinguish three zones as a function of the stress intensity, fault direction, and the value of the temperature anomaly (Figure 3). The brown zone and the green zone on Figure 3 correspond to a ratio R [1-200]. The red zone corresponds to a ratio R [200-400]. For this permeability ratio, the temperature anomalies will be between 88 and 150°C. For the lowest permeability ratio (R [1-200]), temperature anomalies are between 7 and 88°C. For these values, two convective regimes are observable. Firstly, for stress values below 40 MPa and for a fault direction below 50°, the fluid flow (indicated by the black arrows) is defined by an upward movement in the center and downward movements at both ends. This convective regime occurs along two dimensions of the space (along the z and x axes). The bulging of the isotherm is the consequence of this fluid circulation pattern, which follows a “blob-like” pattern. Secondly, for stresses greater than 40 MPa and for a fault direction greater than 50°, the fluid flow is also defined by an upward movement in the center and downward movements at both ends. However, compared to the blob-like convective pattern, the downward movements are more concentrated around the upward movement. This convective regime is expressed along two dimensions of the space (along the z and x axes). The deformation of the isotherm is the consequence of the fluid circulation which follows a “finger-like” pattern. For the highest permeability ratios (R [200-400]), we find a continuous upward and downward motion in all three dimensions of space. Circulation of warmest fluids is along the z and y axes, while the circulation of the coldest fluid is along the z and x axes. This circulation of fluids occurs according to a “double-like” pattern.

As we have seen, the parameters influencing the formation of these convective patterns are the permeability, intensity and direction of the stress. For high permeability ratios R [200-400], the poroelastic effects due to stress state variation have no significant effect on fluid flow pattern. However, for lower permeability ratios R [1-200], changes in the fluid flow pattern can be observed depending on the stress direction and stress intensity. Thus, it could be interesting to consider these different parameters in the exploratory phase. The results of the parametric study show that the final volume occupied by the temperature anomaly is higher for a "blob-like" convective regime than for the two other identified regimes. More precisely, for the simplified used boundary conditions, vertical deformation zones, which have an angle of 30 and 70° with respect to the boundary stress, will concentrate the highest temperature anomalies, at the lowest depths (for more details see Duwiquet et al. 2021; Duwiquet, 2022). This simplified and idealized model illustrates the impact of mechanics with one boundary stress only. The effects are expected to be greatly emphasized under anisotropic boundary conditions because of the shearing conditions they introduce.

2.2.2 Tectonic regimes as a control factor for Crustal Fault Zone geothermal reservoir

By considering a simple geometry and idealized hypotheses, it can be seen that the stress direction, the stress intensity, and the permeability ratio between the fault and the basement are parameters that have an influence on fluid flow and consequently on the intensity and depth of the temperature anomalies. Thus, a way to improve the 3D models would be to consider permeability as dynamic parameter that varies in response to different geological processes, including varying tectonic regime. It would then be possible to identify a mechanical process(es) that could impact the fluid flow. In order to better understand the role of stresses and their effects on fluid flow and the consequences they may have on temperature anomalies, we considered more realistic boundary conditions and a dynamic permeability adapted to the fractured medium.

Here, we investigate the role of tectonic regimes on the formation of geothermal reservoir, within a CFZ and without any other heat source other than the natural geothermal flux (amagmatic system). We propose a 3D THM numerical model with a simplified geometry. The physical properties and the hydraulic permeability in the model are adapted to the fractured environment. To understand the role of tectonic regimes, we first considered a benchmark experiment that neglects tectonic stress which will be our reference model (for more details see Duwiquet et al. submitted; Duwiquet, 2022).

To investigate the influence of the tectonic regimes on fluid flow, we build models based on the same physics as the reference model's plus we use mechanical boundary conditions corresponding to the evolution of the stress with depth for different tectonic regimes. For this, we refer to an Andersonian assumption—where the principal stresses are expressed with vertical S_v, maximum horizontal S_{Hmax} and minimum horizontal S_{hmin} components—which is regularly used in geomechanical studies of reservoirs (Anderson, 1905; Zoback et al. 2003):

- Compressional (reverse/thrust faulting), $S_{Hmax} \geq S_{hmin} \geq S_V$
- Extensional (normal faulting) with, $S_V \geq S_{Hmax} \geq S_{hmin}$
- Strike-slip, with, $S_{Hmax} \geq S_V \geq S_{hmin}$

With the aim to understand the possible effects of stress intensity, stress-depth profiles were collected on two natural systems, one in the French Massif Central, and one near the San Andreas Fault (USA). Two cases are considered, a low stress intensity zone (e.g. French Massif Central) and a high stress intensity zone (e.g. San Andreas Fault). It should be noted that we assume that regional stresses prevail over local stress variations, which is consistent with our homogeneity assumption. In the case of this study, we will present only one result of the two intensities tested. To see the effects of intensity and its discussion, see Duwiquet (2022).

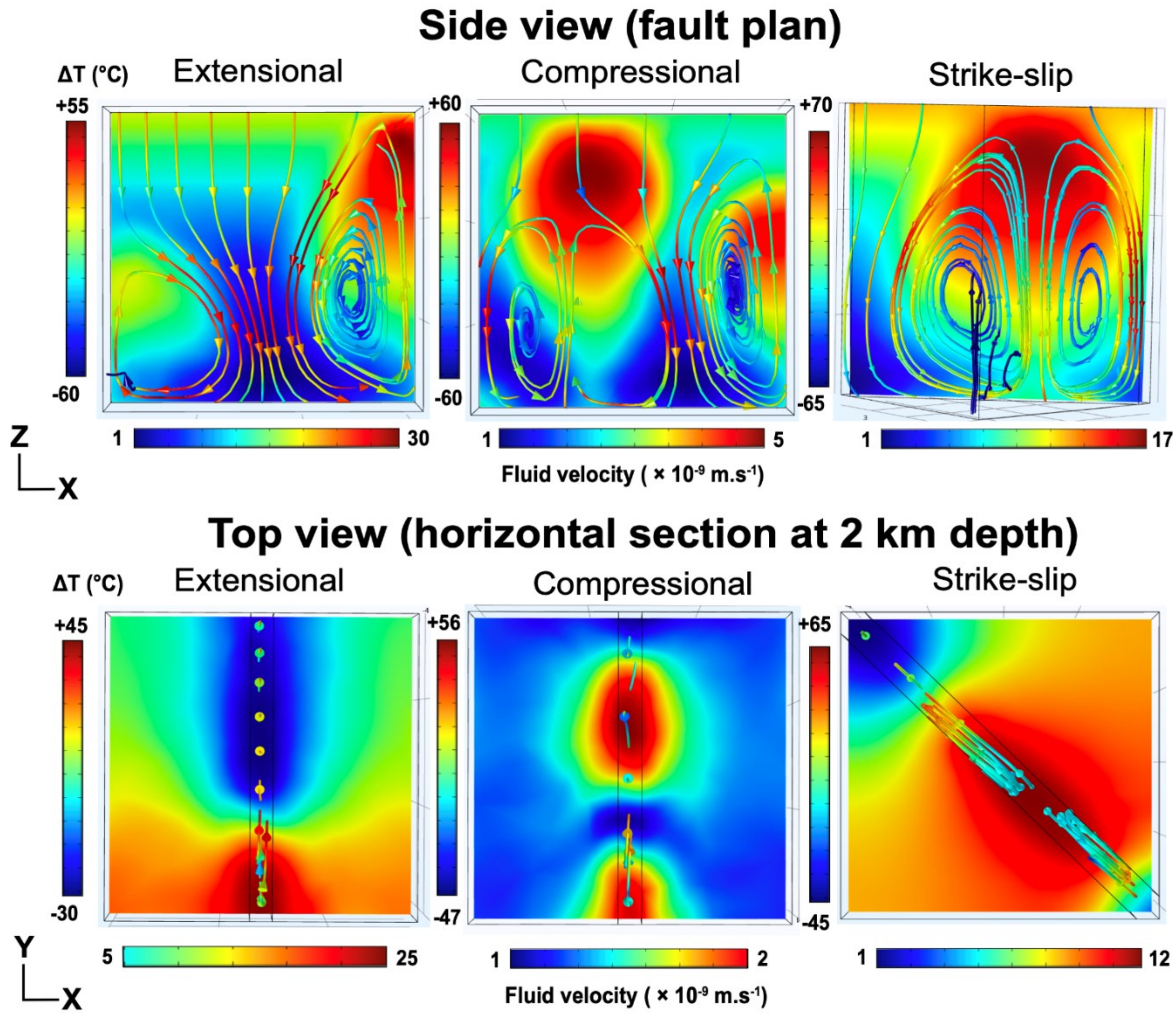

Figure 4 : Results of numerical modelling after stresses application (for more details see Duwiquet, 2022). The results are shown in vertical section (Side View, located in the middle of the fault) and in horizontal section, (Top view, located at 2 km depth). The scale of temperature anomalies and fluid flow velocities is different according to the tectonic regimes. For each regime, the maximum and minimum values of temperatures and fluid flow velocities are indicated. Positive temperature anomalies are colored red, negative temperature anomalies are colored blue. Fluid circulation is marked by the lines, the direction by the arrows. The color of the lines corresponds to the fluid velocity. In red the velocity is the highest, in blue the velocity is the lowest.

Regardless of the considered tectonic regime, positive and negative temperature anomalies are observed. They differ by their number, intensity and lateral extension (Figure 4).

In extensional tectonic regime, two positive temperature anomalies are found. The highest is +55°C and the lowest is +10°C. A negative temperature anomaly at the center of the fault is found. This anomaly is -60°C. At 2 km depth, the horizontal cross-section shows a negative temperature anomaly that reaches a maximum of -30°C. This anomaly covers a large surface area of the fault. The positive temperature anomaly of +45 °C occupies the remaining space, but extends further into the basement. In the basement and up to the edge of the model, we find a positive temperature anomaly of +20°C. The fluid flow pattern is characterized by a downward movement at the center of the fault and two upward movements at the ends of the fault. The minimum fluid velocity is 5×10^{-9} $m.s^{-1}$ and the maximum is 30×10^{-9} $m.s^{-1}$.

In compressional tectonic regime, we find two positive temperature anomalies. The value of the maximum temperature anomaly is +60°C. The second temperature anomaly is +40°C. In horizontal cross-section, the values of these two temperatures anomalies are +56 and +47°C, respectively. The lateral extension of these temperature anomalies is limited. They are surrounded by negative temperature anomalies that locally reach -47°C. At a depth of 2 km, the positive temperature anomalies are much less extended than in extensional tectonic or strike-slip regimes (see below). There are two upward and two downward movements. The minimum fluid velocity is 1×10^{-9} $m.s^{-1}$ and the maximum is 5×10^{-9} $m.s^{-1}$

In strike-slip regimes, positive temperature anomaly extends widely along the length of the fault, from the surface to 4.5 km deep. The maximum positive temperature anomaly value is +70°C. Temperature anomalies of 25°C are found in the basement suggesting that, for strike-slip system, the positive temperature anomaly represents a large volume. This heat propagation is achieved by thermal diffusion from the fault center, where the temperature anomaly is the most intense. Indeed, the larger the convection cell inside the fault, the wider the extent of the diffusive perturbation. At 2 km depth, the maximum value of the temperature anomaly is +65°C. Negative temperature anomalies are present and localized at the extremities of the fault. The fluid flow pattern is characterized by an upward movement at the center of the fault and two downward movements at the ends of the fault. This convective fluid circulation pattern was previously (Figure 3) called "blob-like". In Figure 4, the temperature anomaly extends largely in the basement. This is not the case for the other convective models. The minimum fluid velocity is 1×10^{-9} m.s^{-1} and the maximum is 17×10^{-9} m.s^{-1}.

Tectonic regimes influence the distribution and the amplitude of temperature anomalies. Positive temperature anomalies are most intense in strike-slip, then in compression and extension. The spatial extent of positive temperature anomalies is not identical for each tectonic regime. In strike-slip, these anomalies are largely extended through the basement. This lateral extension is less pronounced in the extensive tectonic regime. Finally, in a compressional regime, these anomalies are localized in the near vicinity of the fault. The tectonic regimes have a key role in the temperature distribution, and this is clearly related to the different convective patterns and fluid flow velocity, as described below. In reply to the application of different tectonic regimes, the fluid pressure for each tectonic regime is different. Now the convection is not only linked to buoyancy forces, but also to what we call "poroelasticity driven force". The convection is here forced (for more details see Duwiquet, 2022).

Finally, by considering simplified geometries and realist physical properties, we have highlighted the role of the dip of geological structures, the stress intensity and stress orientation, and the tectonic regime on the geothermal potential of a CFZ. These elements can be considered in an exploratory phase of these potential targets. Obviously supplementary studies could put forward other parameters to be considered during the exploration. For example, consider the key role of fault intersection, or the thickness of the deformation zone (see perspectives part). The second step of this work consisted in studying the geothermal potential in the field, of a large and deep deformation zone, the CFZ at Pontgibaud (French Massif Central, France). We can then try to apply the results of the previous parametric studies on a natural system.

3. GEOTHERMAL POTENTIAL OF PONTGIBAUD CRUSTAL FAULT ZONE (FRENCH MASSIF CENTRAL) – A MULTIDISCIPLINARY APPROACH

TLS-Geothermics, a French geothermal exploration company, is keen to improve the knowledge of its Exclusive Research Permit (PER) of "la Sioule" licence (Puy de Dôme, French Massif Central). This licence hosts a 3 km-wide and 30 km-long mineralized fault zone (the Pontgibaud fault zone) close to a granite body (the Gelles granite; Négroni, 1981) and where CO_2-rich thermomineral resurgences are present. In the Pontgibaud area, the geothermal gradient near the surface is 37-41 °C/km (International Heat Flow Commission database). Pontgibaud is therefore considered an ideal first case study for the exploration of the high-temperature geothermal potential of CFZs.

Bounded to the East and West by the Aigueperse Saint Sauves fault and the Sillon Houiller fault, the "La Sioule" licence (Figure 5) is largely affected by late Variscan tectonics. Metamorphic formations and the Gelles granite, which are intrusive, characterize the field. Magmatic and hydrothermal veins are widely represented. Covering a large part of the mapped region, metamorphic formations (green in Figure 5) can be separated into different lithologies. Biotite and sillimanite paragneiss extend southwards near the Miouze River and northeastwards to the Villelongue region. Orthogneiss associated with biotite and sillimanite paragneiss are present sporadically. Cordierite gneisses are more widely represented, but it is difficult to assign a cartographic boundary. Rare amphibolitic levels are interspersed in the cordierite gneisses. As an intrusive in metamorphic series, the porphyroid granite of Gelles (red in Figure 5) extends southwest of Pontgibaud, between the Sioule Valley to the East and the village of Tortebesse to the West. To the North, the last granitic points appear immediately to the West of La Goutelle.

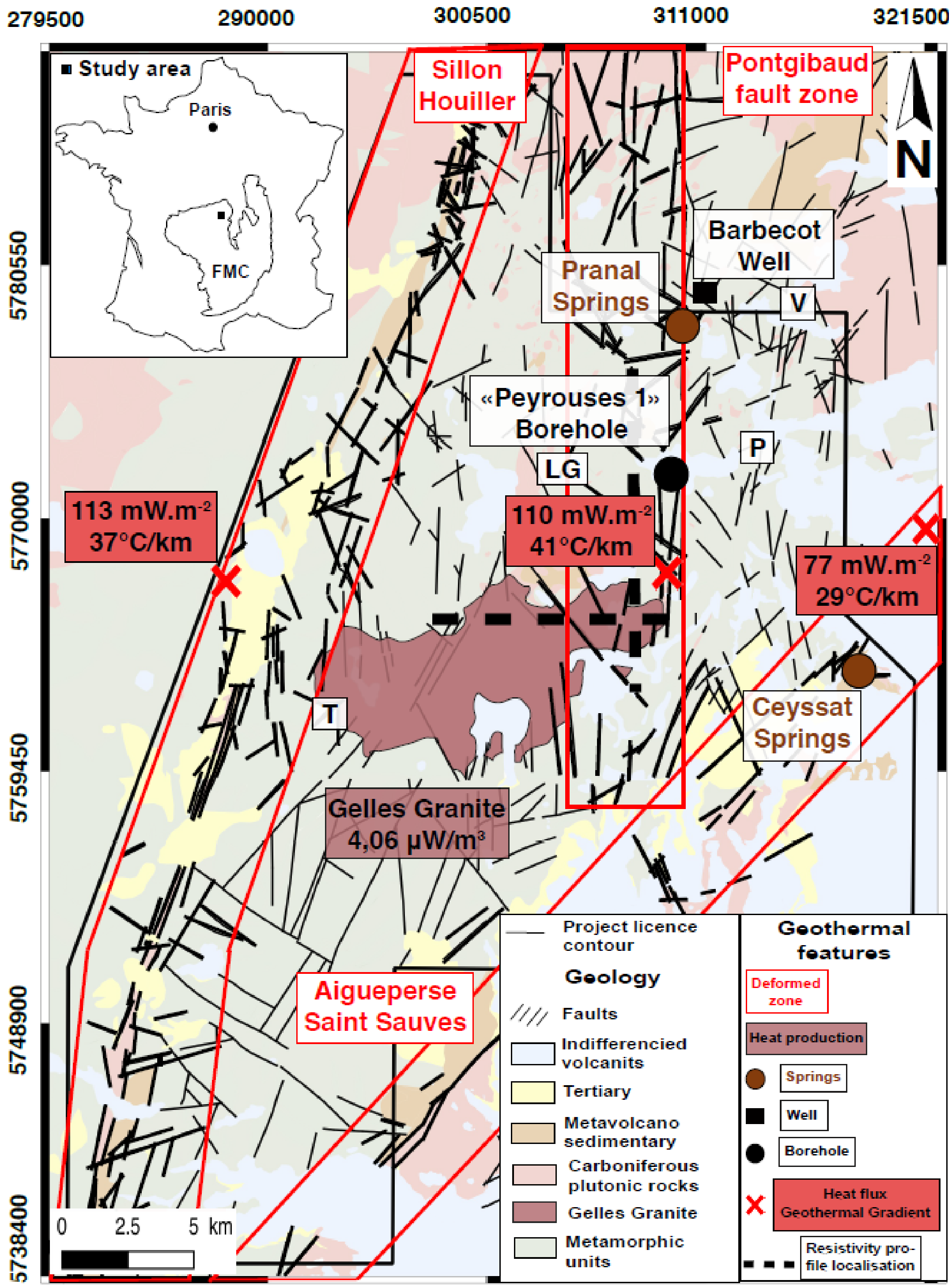

Figure 5 : Geological and geothermal features in the "La Sioule" licence area (black contour). FMC: French Massif Central. Heat flux and geothermal gradient (red crosses (Lucazeau and Vasseur, 1989; Vasseur et al. 1991), International Heat Flow Commission). Heat production (Lucazeau, 1981) and resistivity profile (black dashed line (Ars et al. 2019)). P: Pontgibaud; LG: La Goutelle; V: Villelongue; T: Tortebesse. Coordinate system: WGS84 Pseudo-Mercator EPSG:3857 (after the 1/50,000th geological map published by BRGM).

3.1 Structural setting

In order to understand the spatial organization of potential drains of some geological structure, it is necessary to first consider the tectonic evolution of the study area. A paleostress orientation in the "La Sioule" licence since the Tournaisian (360 Ma) is detailed in Duwiquet et al. 2021; Duwiquet, 2022. At the present-day, the axis of maximum horizontal stress is oriented near NW-SE. Previously we have seen that the stress orientation has an impact on the fluid circulation and has consequences on the temperature anomalies. Therefore, we will use the NW-SE stress orientation in our large-scale numerical models.

3.2 Field, thin-section and X-Ray microtomography observations for permeability spatial variation (X, Y)

When examining different outcrops of the Pontgibaud CFZ, all lithologies show a large range of facies from unaltered and undeformed rocks to altered and/or fractured rocks. Breccia, fractured zones, cataclasites and mineralized veins are noteworthy (Figure 6). These mineralizations are markers of the paleo-circulation of fluids. Samples were acquired from the "Peyrouses 1" borehole located within the Pontgibaud fault system (location shown on Figure 5). Microstructural observations made on thin-sections of these samples mainly show fractured and altered facies. Voids are located within the fracture networks (present in red, Figure 6). Secondary mineralization is present at the borders of voids, thus ruling out the possibility of an anthropogenic origin of these voids during the manufacturing process of the thin sections. Some of these fractures are totally sealed, and therefore may provide barriers to fluid flow, while others show voids, thus conferring a potential permeability to the system. We therefore observed evidence for potentially high- and low-permeability zones within the fault system. At this scale of observation, all the fractures seem to form a dendritic network. This type of network is largely detailed in previous studies (Reis, 2006; Lorenzini et al., 2011) and would be present in systems with intense fluid circulation (Bejan and Lorente, 2006).

In order for fluids to circulate, it is necessary that these voids are connected in 3D. In order to verify this, the same samples were scanned and analyzed by X-Ray computed tomography at the Institute of Earth Sciences in Orleans (ISTO). The 3D observations (Figure 6) show, in yellow, the walls of mineralization in which some voids are taken into account and in red the mineralization (here galena (PbS)). The presence of voids is marked at the heart of some mineralization and at the levels of the mineralization walls. Moreover, these planes seem to be connected in three dimensions, thus potentially facilitating fluid circulation.

3.3 Borehole observations and permeability measurements for permeability spatial variation (X, Z)

Sampling was made on different lithological facies present in the "Peyrouses 1" borehole. The averages values of the permeability, measured in the laboratory, of intact, fractured, altered, fractured and altered facies are 2.8×10^{-16}, 3.9×10^{-15}, 1.5×10^{-15}, and 3.1×10^{-13} m^2, respectively. In order to observe these permeability variations according to the different facies and depth, we have transcribed these average values into a permeability/depth profile (Figure 7). This profile provides additional constraints on the variation of permeability from 0 to 250 m. We can then try to incorporate these permeability variations into our numerical model.

Depth-dependence of permeability follows the equation of Garibaldi et al. (2010). This equation makes it possible to consider the effect of depth on permeability. By zooming on the first 250 m, permeability variations in the order of 10^{-16} to 10^{-13} m^2 can be observed (Figure 7). This variation is of the same order of magnitude as that measured in the laboratory. It is not surprising that the permeability variation of the numerical models does not exactly follow the variation present in the borehole. Moreover, the results of Figure 7 do not exactly reflect the exact values, since we have inserted the averages of these measured values. Nevertheless, we will keep the assumption that general trends are respected.

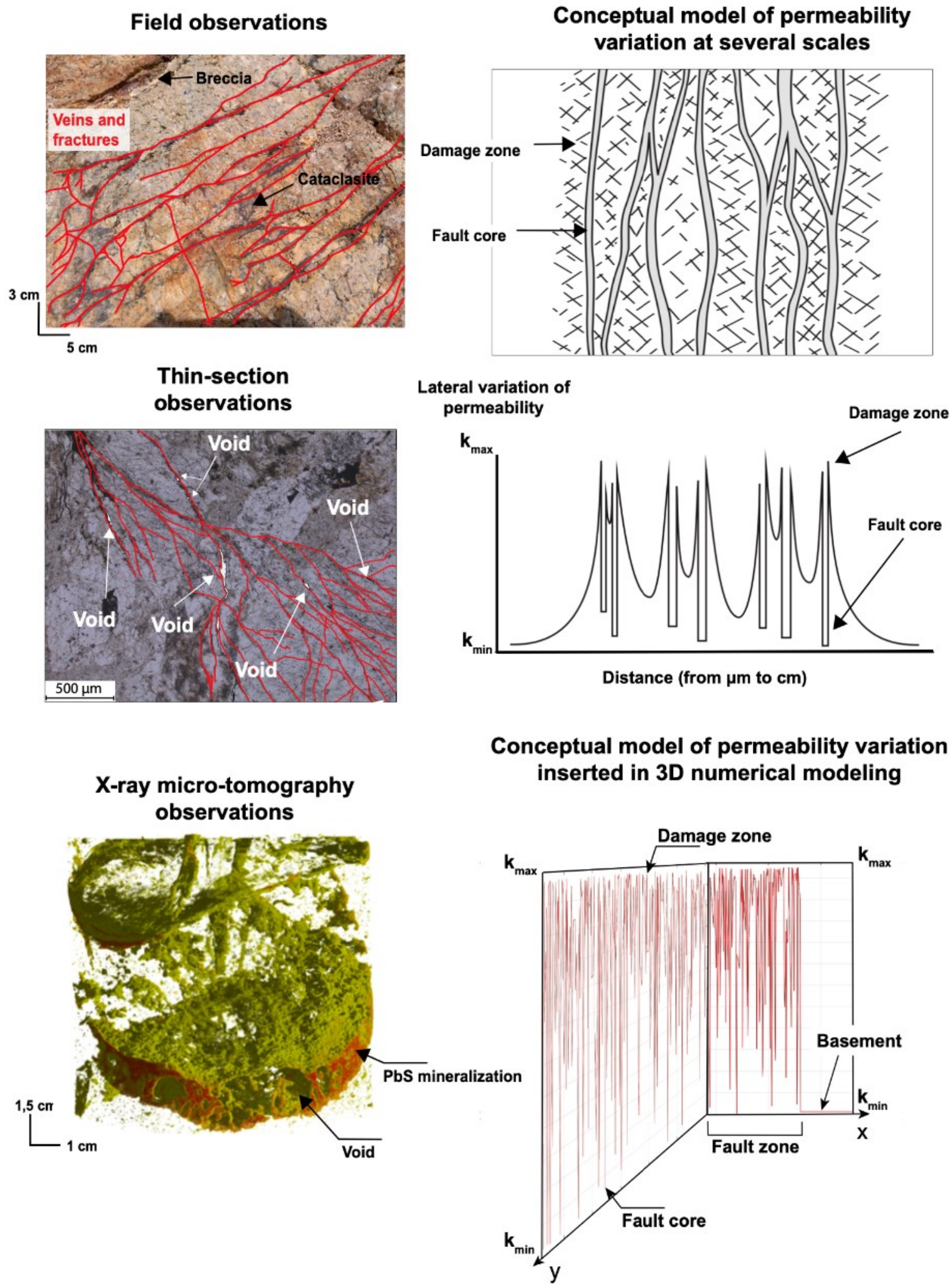

Figure 6 : Field and laboratory observation (left). Incorporation of the multiple fault core conceptual model (Faulkner et al. 2003) within numerical modelling done with Comsol Multiphysics™ (right). The resolution of the X-ray micro-tomographic image is 10 µm.

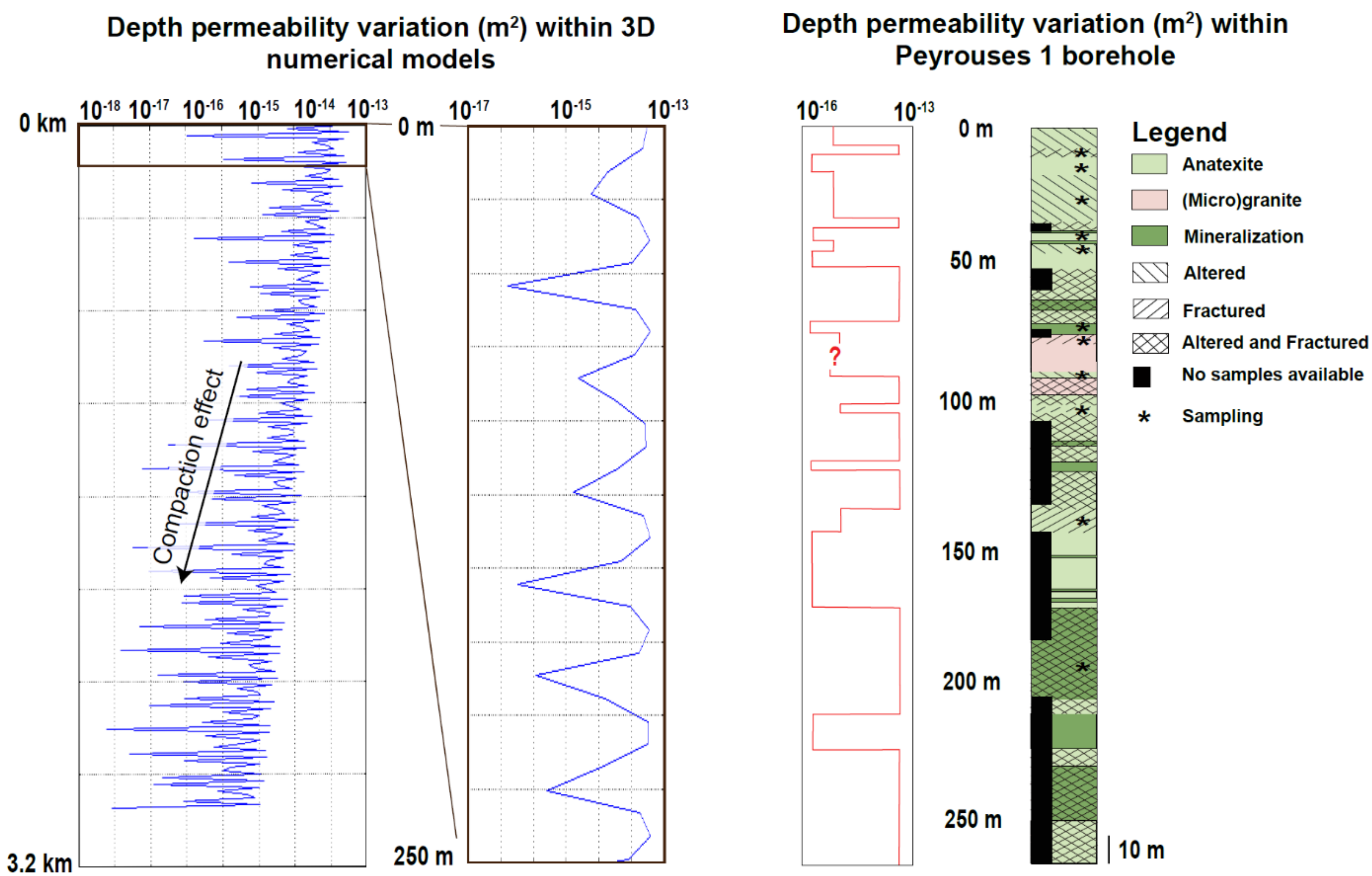

Figure 7 : Permeability variation along the x and z axes and comparison with the average permeability value of samples representing different facies taken from the Peyrouses 1 borehole (see location on Fig 5).

3.4 Integration of permeability variation (X, Y, Z) in numerical models

The conceptual model of Faulkner et al. (2003) describes damage zones (high permeability zone) and fault cores (low permeability zone), as shown in Figure 6. Considering the close correspondence between the variations in potential permeability of the different observations made with the conceptual model of Faulkner et al. (2003), we propose to integrate this permeability variation into our numerical models along the two horizontal axes, x and y (Figure 6, Eq 1 and 2). Equations 1 and 2 include a lateral variation of permeability within the fault zone in order to reproduce the high permeability zones (damage zones) and low permeability zones (fault cores).

Field and laboratory analyses indicate that the Pontgibaud area has a very high fracture density. By keeping the usual depth-decrease of permeability, a lateral variation can be included, by using the following spatial variation:

$$K_F(x, y, z) = K_{F0} \times f(z) \times f(x, y, z) \quad (1)$$

Here $K_F(x, y, z)$ is the fault permeability dependent on the three space directions (m^2). K_{F0} is the permeability at the surface (m^2), $f(z)$ is the depth-dependent function and $f(x, y, z)$ makes the permeability alternate along a sinusoid applied to the three axes of the numerical model, such as:

$$K_F(x, y, z) = K_{F0} \times \left[exp\,\frac{z-800}{\delta}\right] \times \left[201 \times \sin\left(2 \times \pi \times \frac{(x+y+z)}{\lambda}\right)\right] \quad (2)$$

The term λ corresponds to the wavelength of the sinusoid. To reproduce rather fine alternations of high and low permeability, as suggested by field and laboratory observations (see Figure 2), a low value of λ was chosen (Duwiquet et al., 2019a; 2020a; 2021a). The length δ (m) characterizes the intensity of the decrease in permeability with depth.

4. FIELD, LABORATORY AND NUMERICAL EXPERIMENTS SYNTHESIS OF THE PONTGIBAUD CFZ

The global geometry of the Pontgibaud system is synthesized in Figure 8A. It includes structural measurements detailed and discussed in Duwiquet et al. (2021). To put it in a nutshell, the Pontgibaud system is characterized by a large deformation zone (> 3 km), mainly defined by North-South structures, and crossed by E-W, NE-SW, NW-SE and some other NNE-SSW structures.

Thin-section (2D) and X-ray microtomography (3D) observations have revealed spatially propagating fracture networks in which fluids can flow through pores at different scales, from 2.5 µm to 2 mm. According to Bejan and Lorente (2011), architectures at different scales and arranged in a hierarchical pattern would promote fluid flow. These natural drainage systems (Figure 8b) may have lower flow resistance than a similarly porous volume. The constructal theory (Bejan and Lorente, 2006) allows us to describe the natural tendency of flow systems to generate multiscale shapes and structures favoring fluid flow. It has also been shown that the transition between heat transfer at the nanoscale and more conventional scales is governed by the smallest dimensions and by their spatial heterogeneities (Gosselin and Bejan, 2004). The origin of these heterogeneities could be the stress (with tectonic comminution) and the water (with fluid pressure). Finally, with knowledge of current parameters, the geometry of the Pontgibaud CFZ might correspond to an optimal one, which facilitates efficiency of convective flow.

This 150°C rise in the isotherm (Figure 8c) is the consequence of fluid ascending to the center of the Pontgibaud CFZ and descending at its extremities. This convective pattern was defined in the study as the blob-like convective pattern (Figures 3 and 4). This convective pattern was, in this parametric study, obtained for permeability ratios R [1-200], stress intensities below 39 MPa, and an orientation with respect to the main stress between 0 and 50°. When comparing these three parameters, the convective pattern observed in the numerical model of the Pontgibaud area is comparable with the result from the parametric study.

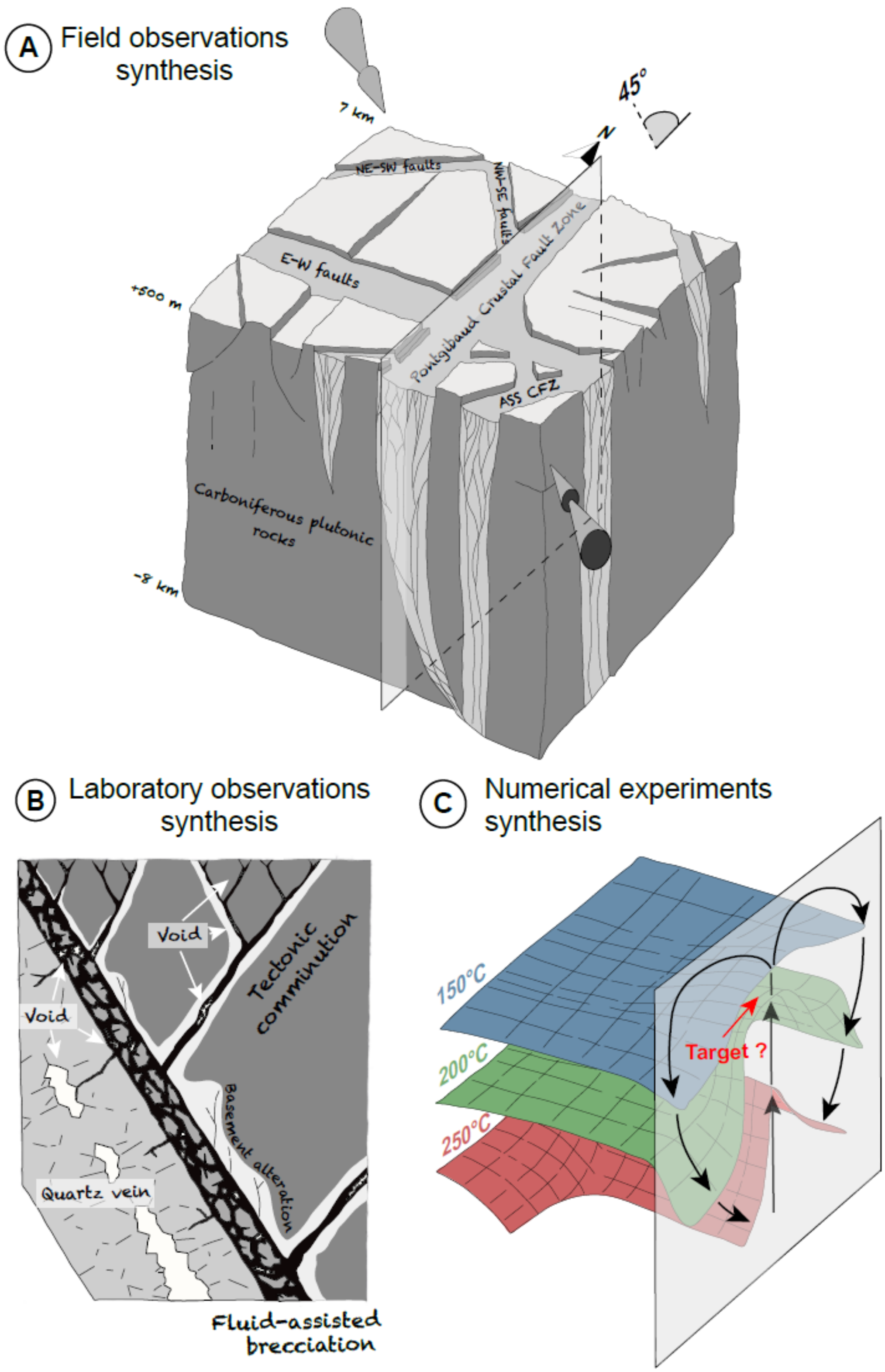

Figure 8 : (a) Three-dimensional conceptual model of the Pontgibaud CFZ as a geothermal reservoir potential. Details of the voids present at different scales and in which fluids can flow. (b) The processes that may be at the origin of these voids (tectonic comminution, fluid-assisted brecciation, and basement alteration) are illustrated. (c) Comparison of the large-scale modelling results with field data shows that fluid could flow through a blob-like pattern and locate the 150°C isotherm at 2.3 km depth.

5. CONCLUSION & PERSPECTIVES

The goal of this thesis is to increase the amount of energy extracted from the subsurface by exploring new targets for high-temperature (T > 150°C) geothermal energy. Due to their permeable and deep nature, CFZs are interesting geological targets in the basement domain. In these zones, the fluid circulation, by convection, depends on a set of elements. Through numerical modelling with simplified geometries and realistic physical properties, we have highlighted those different convective regimes exist and depend on parameters such as:

(i) The dip of the geological deformation zones

(ii) The permeability ratio between the deformation zones and the basement

(iii) The intensity and direction of mechanical stress

(iv) The tectonic regime at work

From the results of these parametric studies general trends can be used in the exploratory phase:

(v) Vertical deformation zones concentrate the highest temperature anomalies at the shallowest depths

(vi) Deformation zones subject to strike-slip tectonic regime concentrate the most intense temperature anomalies with a large spatial extent

These generic results could be compared and applied to a natural system. According to geological and geophysical data, the Pontgibaud Fault Zone (Massif Central, France) is a CFZ hosting a hydrothermal system at a few kilometers depth. Considering a multidisciplinary approach (field observations, microscopic observations, and laboratory analyses) the Pontgibaud CFZ is characterized by a large, sub-vertical, N-S oriented deformation zone intersected by different fault families NE-SW, NW-SE and E-W. This fault network has the characteristics of a dual matrix-fracture permeability reservoir. Observations at different scales (2.5 µm - 2 mm) show draining structures following a dendritic geometry. Constructal theory suggests that this geometry, by limiting resistance to flow, would facilitate fluid flow. Fluid circulation has been characterized by integrating field data, laboratory observations and measurements into crustal-scale numerical modelling. The convective dynamics of these results are comparable to the results of parametric studies. Moreover, comparison of the results of large-scale numerical modelling with field data (temperature, heat flux, resistivity profile) allowed to estimate the depth of the 150 °C isotherm at 2.3 km in the Pontgibaud CFZ.

Other parameters may impact fluid flow and need to be investigated such as, for example, the fault intersections. Evidence of mineralization and fluid circulation is documented in several studies (Craw, 2000; Person et al. 2012). For example, in the Basin and Range, Carlin-type gold mineralization occurs at fault intersections (Hofstra, 2000; Coolbaugh et al. 2005). Numerical modelling of the Pontgibaud fault zone shows that the 150°C isotherm rises through upward movement at the intersection of several fault families.

Moreover, these naturally permeable and deep structures can have variable thicknesses. For example, the Carboneras vertical strike-slip fault zone (Andalusia, Spain) in some places is more than 1 km wide (as noted by previous authors: Rutter et al. 1986; Keller et al. 1995). However, the width of the fault zone can also be 4 km (northeast) where the Carboneras Fault connects the Palomares Fault (Faulkner et al. 2003). In Madagascar, Rajaobelison et al. (2020) show that conceptually the Ambanja geothermal reservoir would be located at a deformation zone, characterized by three families of subvertical faults over a thickness greater than 4 km. Malkovsky and Pek (2004) show that the thickness of the fault system is also a key control parameter on the mode of heat transfer. In order to account for the thermicity of the environment, this parameter could be tested with numerical modelling.

Finally, based on a multidisciplinary approach, we hypothesize that CFZs represent potential reservoirs for high-temperature geothermal exploitation. These results will be further investigated in future work and may consider, for example, more constrained models (with further sensitivity analyses). These trends also need to be confirmed by operator drilling. If this potential is confirmed, then this concept could be used in other study areas: Badenweiler-Lenzkirch Sutur (Germany), the Longmen Shan fault zone (China), the Pasmajärvi fault zone (Finland), the Keumwang fault (South Korea), etc. This georesource could then accentuate its role in the energy transition required to address the ongoing climate crisis.

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