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# Naturally fractured granites as promising targets for HT geothermal exploration: Impact of fault network geometry.

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## Introduction

Currently, French geothermal power plants are limited to tectonically active areas such as the Rhine graben (Soultz-sous-Forêts) or magmatic zones (Bouillante, Guadeloupe). In order to increase the production of resources (heat or power), geothermal exploration must move towards other geological contexts, such as basement areas. However, direct exploitation remains complex because of low porosity and permeability values (Achtziger-Zupancic 2017). However, the tectonic history of these areas including fault reactivations, may promote the formation of major fault zones, whose impact on fluid flow has already been demonstrated in numerous studies (Barton et al. 1995; Faulds et al. 2010). Although they may represent significant geothermal reservoirs, their exploration and exploitation remain limited. It has been demonstrated that fault zones may host positive temperature anomalies at shallow depths (Duwiquet et al. 2021, Penhoët et al. 2024), resulting in lower drilling costs.

To enhance the understanding of the geothermal potential of these unusually permeable targets, our study will concentrate on two fault zones located in a crystalline basement : the Margeride Granitic Complex (MGC), in the south of the French Massif Central. Vasseur et al (1997) identifies its northern edge as a potential geothermal reservoir that would feed the 30 hot springs in the village of Chaudes-Aigues (e.g. the Par spring, with an emerging fluid temperature of 82°C). According to different geothermometers, the fluids would reach 200°C at a depth estimated at 2 500 metres by Vasseur et al. (1997). A 2.5 km wide N140 fault zone drains surface water to depth and then towards Chaudes-Aigues. The N140 fault zone intersects another N30 fault zone at the location of Chaudes-Aigues. Twenty kilometers east of the Chaudes-Aigues area, various geothermometers applied to the Coren-les-Eaux spring (Saint-Flour area, Figure 1) have also identified a potential reservoir of up to 220°C (Fouillac 1983). This spring would be associated with our second case study, the Margeride Fault Zone (MFZ).

## Geological settings

The basement is composed of metamorphic gneissic formations (Vanderhaeghe et al. 2020; green in Figure1). The MGC emplaced around 323 Ma ago by NW-SE faults (feeder zones) (Talbot 2005). During the extension phase at the Eocene, small sedimentary basins visible in the western part of the MGC have been formed (De Goer De Herve et al. 1990; yellow in Figure 1). The MGC and gneiss units have suffered successive tectonic brittle events from the late Paleozoic to present-day (Faure 1995).

## Methods

### 1. Field and GIS

A regional scale fault density analysis has been performed after assembling the 15 geological maps covering the study area. The method consists in creating a grid of 500-metre squares and adding up the length of the faults in each cell. Results were divided into 5 classes using the natural breaks of the distribution histogram (Jenks algorithm implemented in QGIS). These results were compared with observations made in the field.

### 2. Numerical modelling

The MGC offers two sectors with a possible high geothermal potential: the Chaudes-Aigues fault clusters and the Margeride fault zone (MFZ, Figure 1). As demonstrated in previous studies, the geometry of the fault, more specifically its thickness over height ratio, directly influences the setting up of thermal convection (Malkovsky and Magri 2016). These two sites will be used for parametric studies: firstly, a Y-shape model to represent the intersection of the fault clusters in the Chaudes-Aigues area; secondly, a prism model to study the impact of the varying thickness in the longitudinal direction. As in Guillou-Frottier et al. (2013) Darcy law was coupled with heat transfer equation and mass conservation. Thanks to field observations and literature data, several variables necessary for the modeling were estimated.

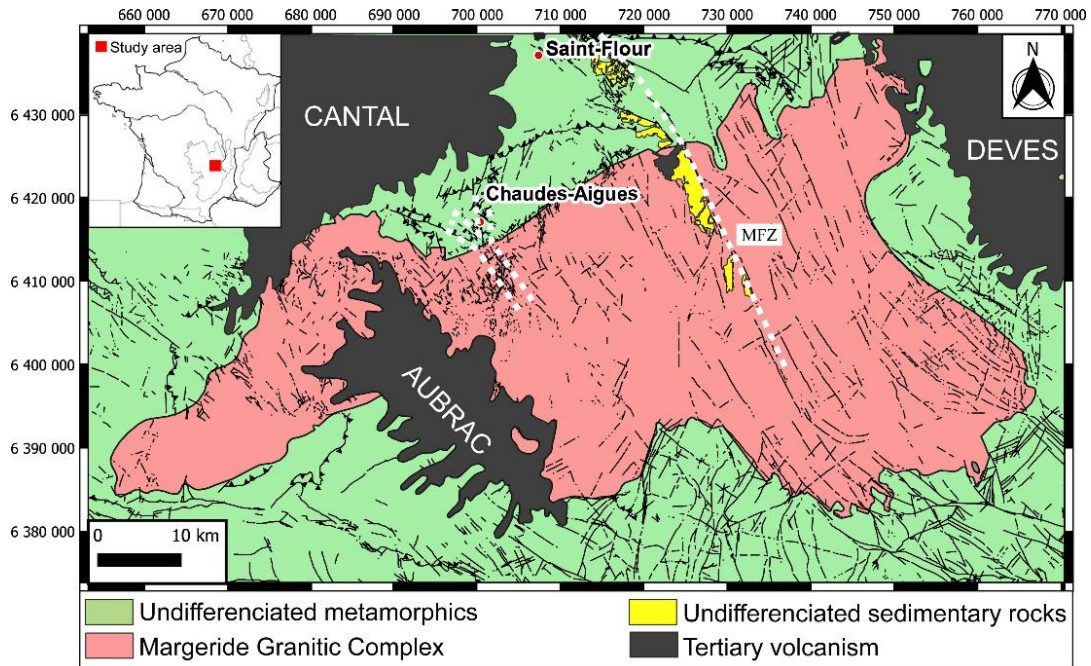


Figure 1: Simplified geological map of the Margeride Granitic Complex (MGC) White dashed lines indicate the simplified geometry used for 3D models. Coordinate system: Lambert 93 – RGF93 EPSG:2154.

## Results

### 1. A densely fractured granite.

An analysis of fault density on a regional scale highlights the main damaged zones. Most of the MGC is characterised by densities ranging from very low to moderate. However, large alignments corresponding to N140 faults can be seen. These structures displace the feeding zones of the granite during its emplacement (Talbot 2005).

The village of Chaudes-Aigues is characterised by high fault density. This zone corresponds to a thick N140 fault zone extending into the granite (Figure 1). Its extent is minimised here because the southern part is covered by morainic sediments.

Another area of high density can be seen around Saint-Flour, corresponding to the thick part of the MFZ. It is more difficult to identify the southern part (low density value) because of its reduced thickness (Penhoët et al., 2024).

The very high fault densities located in the south of the MGC are mainly due to a change in lithologies (Jurassic sediments), which do not have the same rheology as the basement rocks. The same observation can be applied to the southern part of the Cantal volcanic complex and Tertiary sediments. The highly faulted section to the east of Saint-Flour corresponds to the thrust between the two gneissic units.

### 1. Two potential geothermal reservoirs.

Numerical models using a prismatic model have shown that there is always a positive temperature anomaly in the thickest part of the MFS. At Saint-Flour, a temperature of 100°C could be expected at a depth of 1000m (positive temperature anomaly of 60°C) (Penhoët et al., 2024).

To investigate the influence of fault intersections, as at Chaudes-Aigues, Y-shaped models were carried out. The results indicate a positive thermal anomaly at the point where the fault zones intersect. At the surface temperature reaches 82°C, reproducing the Par spring temperature (Figure 3a). At a depth of 1000 m, the anomaly intensifies to reach 108°C (Figure 3b). As a result, the 150°C isotherm (target temperature for exploitation) rises more than 3 000 m to reach a depth of 1 500 m (Figure 3c). Over time, the anomaly moves towards the extremities of the fault zones and its intensity decreases.

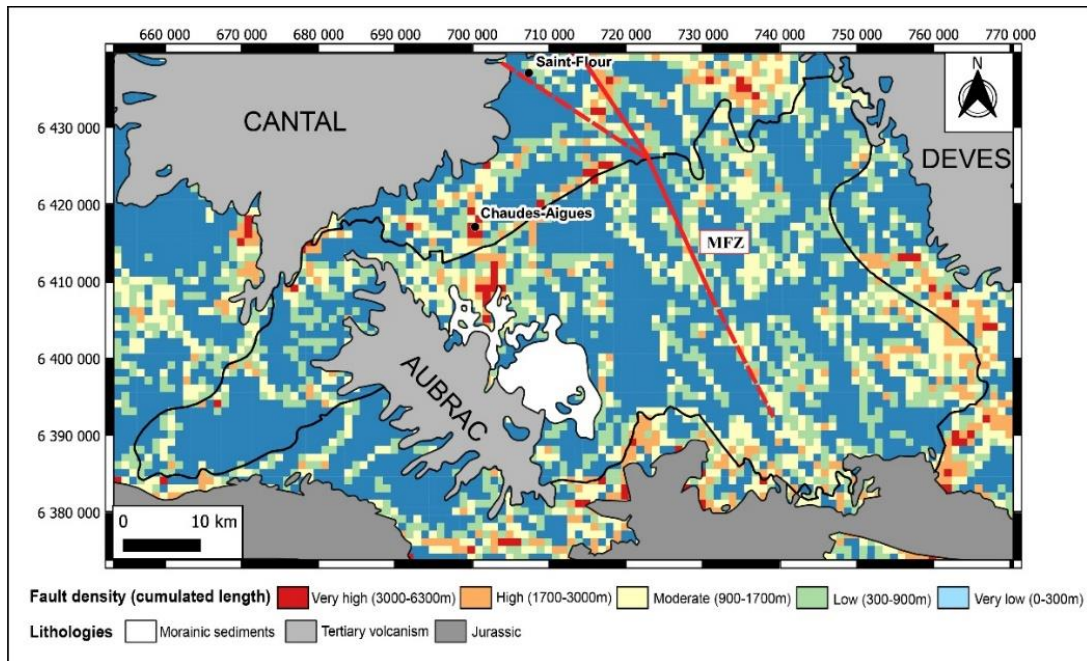


Figure 2: Fault density map of the study area, the contact between lithologies (black) correspond to those shown in Figure 1. Coordinate system: Lambert 93 – RGF93 EPSG:2154.

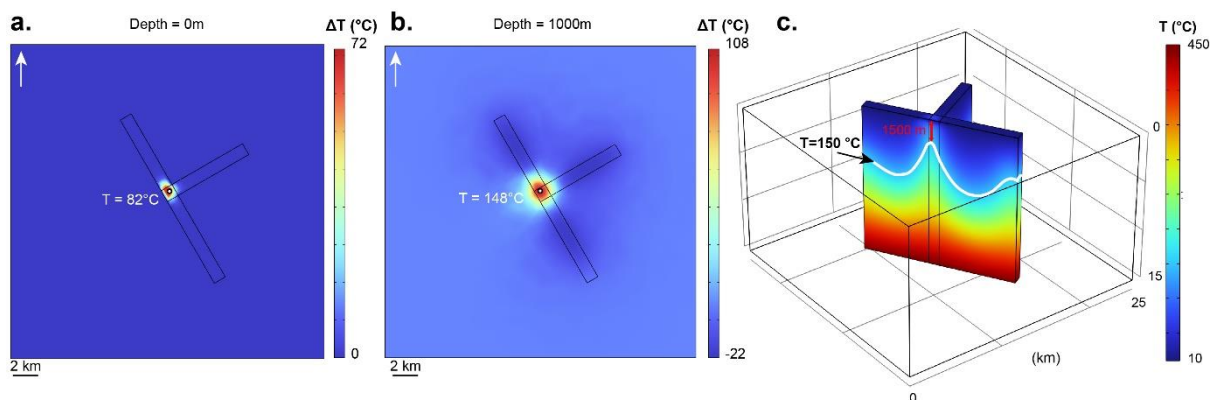


Figure 3: 3D model showing thermal anomalies  $\Delta T$  and values of temperature at the intersection (a) section at the surface, (b) at 1000m depth; (c) 3D view showing isotherm 150°C (white line). All were produced at  $t=400$  kyr and for permeability values of  $10^{-14}$  m<sup>2</sup> in the fault zone and  $10^{-18}$  m<sup>2</sup> in the basement.

## Conclusions

New targets for geothermal exploration can be suggested thanks to this study. The Margeride granite has two potential geothermal reservoirs, offering a resource at much shallower depths than those already identified in sedimentary contexts (Soultz-sous-Forêts, 165°C at 4000 depth). As naturally fractured basement zones are abundant throughout Europe, the high-temperature geothermal potential could be underestimated.

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