Fault-controlled hydrothermal system associated with major Crustal Fault Zone: future drilling target to assess the deep geothermal potential – The Sioule license project

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ABSTRACT

The Crustal Fault Zone concept is a new type of geothermal system defined as a permeable fault zone rooted at least in the brittle-ductile transition zone of the crust. In this case, the high temperature of the deepest part of the fault (>300°C) combined with its high permeability lead to fluid convection into the fault zone. This could allow economic geothermal resources with liquid fluids at 150-200°C at 3km depth without a magmatism contribution. According to our analysis, numerous geothermal power plants can be interpreted as exploiting a CFZ systems. This concept is more widespread than the magmatic ones which dominate the current installed geothermal capacity. Therefore, this new concept could increase drastically worldwide resource assessments and open new geothermal areas to explore.

The Sioule license project, located in the French Massif Central, is a geothermal exploration project which aims to demonstrate the potential of Crustal Faut Zones systems, in a felsic basement without any basin or volcanic layers. The Sioule area was selected for both its CFZ potential and its recent magmatism, in order to minimize exploration risks (a priori heat favorability). The partners of the project plan to drill a deep exploration well beginning of 2021, targeting a favourable intersection involving the Pontgibaud crustal fault zone. Drilling this kind of prospect on the basis of the CFZ exploration concept will be a world first! The potential success of this first well in a CFZ system will lead to explore new prospects without recent magmatism in the Variscan crust. It also allows more precise assessment of the geothermal potential of this context in Europe and beyond.

1. INTRODUCTION

The geothermal systems classification for industrial exploitation proposed by Moeck (2014) is one of the most valuable tools during early stage exploration for new resources. This classification is based on well-known systems and therefore is not very flexible and it is robust only for exploring strictly analog systems.

However, this classification does not consider all the potential new kinds of resources, potentially unproven at this time. As an example, the new concept that we used for our exploration since 2014 (Bellanger et al., 2016; Bellanger et al., 2017), and for which we obtained two research licenses in the French Massif Central (FMC), does not match clearly with one category of the Moeck's classification. Thus, we proposed a new kind of play that we named Crustal Fault Zone (CFZ). This new play could be more common than some plays already detailed by Moeck (2014).

After the presentation of the characteristics of CFZ in terms of intrinsic properties, the European potential and our exploration strategy, we present our exploration results on the Sioule license. The planned drilling in the next years will contribute to support the CFZ sustainability for economic exploitation of 5MWe doublets across European territories.

2. THE CRUSTAL FAULT ZONE CONCEPT

In this part we detail the CFZ concept, we evaluate its potential in Europe in terms of installed power capacity and we propose a dedicated exploration strategy.

2.1 Fault zones, fluids flows and heat transfers

Fault behavior. Fault zones are one of the most permeable features in the crust (Caine et al. 1996; Evans et al. 1997; Curewitz and Karson, 1997; Rowland and Sibson, 2004; Faulds et al. 2010; Faulkner et al. 2010; Bense et al. 2013), especially in an impermeable basement (Belgrano et al. 2016; Achtziger-Zupancic et al. 2016, 2017; Schneeberger et al. 2018). However, conditions governing the permeability of fault zones are multiple. Mazurek (2000) identified the host-rock lithology, the mechanism of brittle deformation, the nature of fracture infills, the degree and the type of hydrothermal alteration, the pre-existing geometry and the internal structure. As an example, a brittle fault zones filled by phyllosilicates (which have a ductile behaviour), have permeability close to 1.10^{-17} m^2 whereas for the same fault permeability is around 1.10^{-13} m^2 where pure brittle faulting dominates (Davatzes and Hickman, 2010). Beyond these inherited minerals/porosity state, current stress field also has a first order impact: brittle fault zones close to their critical stress state (of failure or sliding) are often permeable (Barton et al. 1995). The ductile parts of crustal fault zones are well known to be poorly permeable (< $1.10^{-18,5\pm1}$ m^2) (Ingebritsen and Manning, 1999; Manning and Ingebritsen, 1999). In this kind of zones, where fluids can flow in pervasive ductile matrix, pressure are nearly lithostatic (Connolly and Podladchikov, 2004). However, meteoric fluids from the brittle part of the fault zone can significantly flow in the ductile part, episodically, during a deformation events (Kerrich et al. 1984; McCaig , 1988; Upton et al. 1995). But such kind of dynamics, where permeability could be sustainable during one to hundred years (Ingebritsen and Manning, 2010), could be hard to manage for exploitation needs without additional knowledge.

Fault favorability. Fault zones are more or less favorable for geothermal systems depending on their activity and multiple geological parameters. **Active faults** are faults with displacement and with or without seismicity. **In areas of active extension** this kind of fault is well known to be favorable for geothermal exploitation (Blewitt et al. 2003 ; Moeck, 2014). It is also recognized that meteoric fluids circulate deep in crust along faults (Moeck, 2014) and ascent in favorable tectonic settings (Faulds and Hinz 2015) such as fault intersection and fault termination. One of the most studied area with active extension and geothermal exploitation is the Basin and Range. 39% of the known fault zone geothermal systems in Basin and Range have no surface evidence, but this proportion is probably more than 75% (Faulds and Hinz 2015; Dobson, 2016). This area has undergone a widespread extension during Cenozoic (100 to 200% since 20Ma) associated with scarce felsic magmatism between 45 and 18Ma. It is limited to the Yellowstone plume activity in the Snake River Plain since 17Ma (Camp et al. 2015). Nowadays, the crustal thickness is mainly comprised between 28 and 44km (Gilbert and Sheehan 2002), and the asthenosphere-lithosphere boundary depth between 45 (to the West) and 100km (to the East) (Wang et al. 2002). Extension is active nowadays with slip rate along faults varying from 0.05 to $5mm.year^{-1}$ with displacement per event between 0.1 and 8m (Pérouse and Wernicke, 2017). East of the Basin and Range along the Sierra Nevada, the East Californian Shear Zone has a fast movement toward the NW compared to the Colorado plateau (11.4 $mm.year^{-1}$). It hosts active Core Complexes and geothermal fields like Coso where brittle-ductile transition zone (BDTZ) is lower than 5km depth (Bennett et al. 2003; Monastero et al. 2005). Favorable features for geothermal have also been observed in **active faults in areas with shortening**. Sutherland et al. (2017) have measured a geothermal gradient close to $125\pm55°C.km^{-1}$ suggesting important fluid flows in the Alpine fault zone, which is a plate boundaries with reverse-dextral kinematics. **Active faults in other areas** also seem to be permeable enough for economic exploitation, even if displacements along faults and regional strain rates are low. It is the case for the Upper Rhine Graben (Tesauro et al. 2005; Homuth et al. 2014). Indeed, the Rittershoffen GRT2 well extract a fluid at 177°C, $3.5l.s^{-1}.bar^{-1}$ / $70l.s^{-1}$, 3.2km depth in a fault zone which have a fracture permeability of $5.34.10^{-14}$ m^2 over 40m and a matrix permeability of $9.2.10^{-15}$ m^2 over 460m after soft-stimulation (Baujard et al. 2017; Vidal and Genter 2018). **Passive faults** are faults without displacement and seismicity but which are critically stressed. They are challenging objects for geothermal exploitation because they could be favorable to fluid flows but we are lacking direct observations to assess their economic viability. **Inactive faults** are faults without displacement and seismicity, and not critically stressed. Their permeability only depends to their inheritance (stiff porosity...). Due to the increase of confining pressure, such fault zones have a low probability to be permeable enough from surface to the BDTZ. However, the stronger the rocks (like granite), the better are the chances to preserve fault aperture (Taillefer, 2017).

Fault modelling. If a fault is permeable enough (>5.10^{-15} m^2), convection can occur during long periods (10^3 to more than 10^6 years) and generates heat anomalies (positive and negative) (Rihs et al. 2000; Person et al. 2012; Milési et al. 2018; Duwiquet et al. 2019). The permeability of a fault system is a first order parameter to trigger convection cells and heat transfers. It could be more important than topography and heat characteristics of the crust (like radiogenic heat production or basal heat flows) to create shallow heat anomalies (Duwiquet et al. 2019). Therefore, various crustal scale fault modellings show the ability of this common geological object to create heat anomalies at shallow depth (McKenna and Blackwell 2004; Taillefer et al. 2018).

2.2 The Crustal Fault Zone concept

The CFZ concept postulates that steep crustal (or lithospheric) scale fault zones (at least rooted in the ductile part of the lower crust) could allow fluid flowing within their brittle part, thus inducing heat anomalies (positive and negative). The CFZ concept can be associated to magmatism or not as well as to active fault zone (in terms of current displacement along the fault) or not. The key point that makes CFZ hosting economic geothermal resource is the permeability distribution within the fault zone, in space and time. Indeed, the permeability has a triple influence on the fluid flow, its temperature and the depth of the resource.

A CFZ has large horizontal and vertical dimensions because it is rooted in the BDTZ and spreads on the surface over several tens of kilometers. Therefore, thanks to these dimensions and to its potentially highly fractured internal structure, a CFZ can be a large heat exchanger allowing fluids for exchanging heat along very large surfaces. Such systems are documented by Siebenaller et al. (2013) or Haines et al. (2016). However, these two cases concern (Metamorphic) Core Complex (MCC) contexts. This particular context consists on a quickly exhumed lower crust in dome-like structures under a low-dip detachment fault. It takes place in the upper plate above subduction, where active extension occurs (Jolivet et al. 2004). Such context is recognized in Turkey, USA, Canadian Cordillera, Italy and probably in Indonesia, Philippine, New Zealand, Japan, Mexico... all well known to be among the best places for geothermal exploitation (Roche et al. 2018). MCC belongs to the non-magmatic geothermal plays of extensional domains in the Moeck classification, a class which also include back-arc, pull-apart basins and graben structures. Therefore, the non-magmatic geothermal plays of extensional domain can all be consider as belonging to the CFZ concept.

However, the CFZ concept is larger. As the fault zone could be the reservoir itself (due to its permeability and size), no adjacent permeable layers to the fault zone are required. In addition, permeable CFZ from surface to BDTZ has been proposed for orogenic belt faults like the Alpine fault zone in New Zealand (Upton et al. 1995). Therefore, the orogenic belt class, defined as a conductive dominated system by Moeck (2014) but where deep circulation of meteoric water along deeply rooted faults exist, can be defined as a CFZ system. Beyond active extension and orogenic belt domains, CFZ could occur with magmatism. In such case, the CFZ is the preferred pathway for lava and aqueous fluids and the impact of the magma over the geothermal resource mainly depends on the properties of magma storage and the spatial connection between this storage zone and the CFZ. Finally CFZ could potentially allow resources even in basement context, where no basin, magmatism, high topography or strong deformation/displacement occur.

So, the CFZ concept is ubiquitous and has many characteristics that could lead to the emergence of economical geothermal systems. It is clear that the CFZ-related resources have much controlling factor diversity and consequently offer more possibilities to have economic resources. One of the main advantages is the possibility to free geothermal exploration from magmatic processes which largely dominate current exploited systems but which are unequally distributed on earth, unlike CFZ. The CFZ concept is an additional brick to more accurately assess and increase the geothermal potential of an area. It also allows for defining new potential areas for geothermal development.

2.3 The European potential of CFZ

As it was demonstrated by numerical modeling (e.g. McKenna and Blackwell, 2004), the CFZ only needs to be sufficiently permeable across the brittle crust to host a high temperature - low depth resource. On this basis, a preliminary computation of the geothermal power potential order of magnitude can be realized using: (1) a map of the crustal-scale fault zone, (2) assumption on the percentage of permeable crustal-scale fault zone, (3) assumption on the power which can be installed per CFZ length, (4) a weighting by local known heat flow.

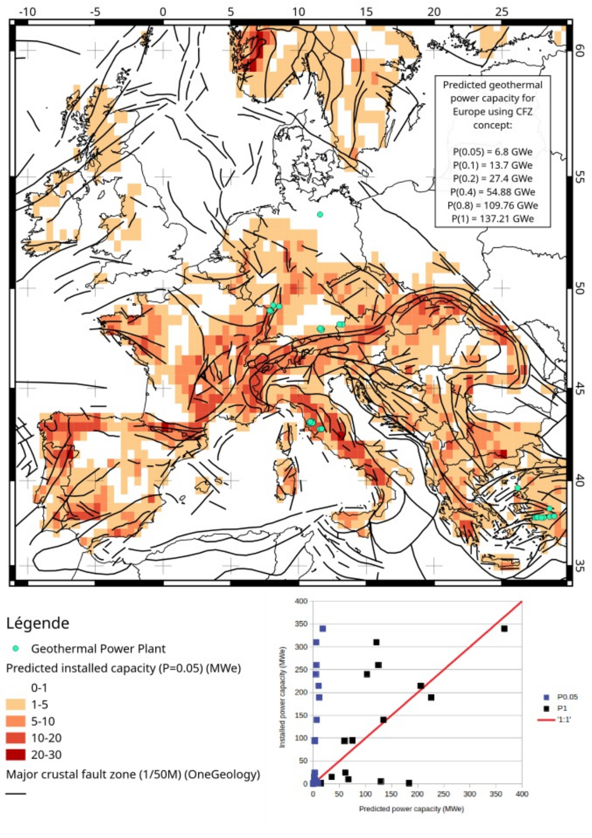

Figure 1: Predicted geothermal power capacity using the CFZ concept, the fault length reported over the 1/1,5M geological map provided by onegeology.org and the heat flows provided by the Global Heat Flow Database. Bottom: comparison between predicted and installed power capacity for p = 0.05 and p = 1.

We calculated the fault length per unit area (0,5°x0,5° cells) according to the fault map provided by onegeology.org (1/1,5M scale) and considered that all reported fault zones have crustal-scale. The heat flows are provided by the Global Database. We have produced different models with different proportion of

CFZ (crustal scale fault zones permeable up to the BDTZ). For each model, we considered that a power capacity of 10MWe could be installed for each 20 km of permeable CFZ length. Finally we have integrated all these parameters in the formula [1] over each 0,5°x0,5° cells.

$$p = ((\text{length(fault)} \times P \times 10) / 20) * (\text{mean(HF)} / 100) \quad [1]$$

With P_{MWe} *= potential power capacity (MWe), L = cumulative length of 1/1,5M mapped faults within the cells (km), p = probability for fault to be a CFZ with (p=[0,05; 0,01; 0,2; 0,4; 0,8; 1]), mean(HF): average heat flow in the cell (= 100 where None) (mW.m*$^{-2}$*).*

At large scale, results (Figure 4) involved potential technical power capacity range between 7 and 140GWe for Europe and between 1 and 28GWe for France. At cell scale, there are consistencies between existing power capacity and potential technical power capacity (Figure 4). Moreover, the areas of interest are different from the one evaluated by GEOELEC or GEODH European projects. Therefore, considering this approach, there is an important geothermal potential in Europe which requires to be evaluated from the CFZ concept point of view.

2.4 Exploration strategy

To assess more precisely the CZF geothermal potential, it is very important to study the current lithospheric architecture (petrology and structures), movement and stress state with the highest possible resolution. Therefore, we need to analyse different possible geodynamical histories and their impact on the lithospheric models. These models can be constrained by large scale geophysical data or used to deduced thermal and mechanical parameter from geophysical data. This kind of work has already been performed by Cloething et al. (2010) over the European lithosphere but with a low resolution which has to be improved.

Despite a large scale study to assess regional potential, it is important to focus on a CFZ with high potential of permeability (see 2.1) to identify its local characteristics. Indeed, the geothermal resource needs to be qualified through consistent model(s) from regional (10^3 km) to local (10^{-3} km) scale. This qualification considers multiple parameters concerning drains (pathways for fluids flows), fluids (type, state) and heat (production, consumption and transfer mechanisms). Such comprehensive study allows for identifying knowledge gaps which could be bridged with new data acquisitions and/or with the comparison of the studied system with analogous existing ones worldwide.

Many tools have to be performed to fill gaps in knowledge and to have an comprehensive analysis: geological mapping, topographic modelling, petrology (mineralogy, structures, …), geothermal gradient wells, magnetotellurics survey and inversion, seismic (MEQ, focal mechanism, tomography), gravimetry, remote sensing (InSAR, spectral analysis...), joint inversion, soil-gas survey, geochemistry (molecular species, elements and isotopes), fluids-rocks interactions, (geothermometry, geochronology). Unfortunately for exploration, hidden geothermal systems are the most common case (Vasseur et al. 1991; Faulds and Hinz 2015; Dobson 2016), especially in presence of cold water table (Dobson 2016). Therefore, all these tools cannot necessarily be used on the explored area. Appropriate choices have to be done regarding the geological context. The available data are then included in a 3D to 4D numerical quantification to test the order of magnitude of various variables under controlled conditions and equations. The most important parameters for economic evaluation are temperature field, fluid flow rate per wells (injectivity and productivity index), and sustainability of the heat extraction.

We have applied this exploration strategy within two geothermal licenses in the French Massif Central (Sioule and Combrailles-en-Marche). The purpose of these licenses is to test the CFZ concept and its exploration in new geological contexts. In order to minimize the risk attached to a new exploration concept, we focused on the Sioule license which is located in an area of hot crust where deep magmatism occurred 9k years ago. However, in case of success (reaching high permeability and temperature in the Pontgibaud fault zone, at 3km depth), future projects can be expected in prospects like Combraille-en-Marche where no recent magmatism is known. We present here below the obtained results before drilling in the Sioule license.

3. EXPLORATION OF THE SIOULE LICENSE

3.1 Settings

The Sioule license is located in the French Massif Central (FMC). The FMC is an area of thin lithosphere (50 to 95km - Sobolev et al. 1997), thin crust (25 to 32km - Zeyen et al. 1997), moderate relief (0,5 to 1,9 km) and is mainly composed by Carboniferous to Permian granites and Devonian to Carboniferous quartzo-feldspathic metamorphic rocks (migmatites, para- and ortho-gneisses and micaschists). These metamorphic series are derived from Ediacarian to Ordovician detritical series and magmatic bodies. The history of this lithosphere can be summarized as follows:

- Clastic sediments were layered between Ediacarian and Ordovician, probably on ocean-continent transition and oceanic crust (leptyno-amphibolic complex) whereas convergence (subduction, arc...) occurred along the Avalonian-

Cadomian belt. These series were affected by extension (rifting) and bi-modal magmatism mainly between early Cambrian to early Ordovician. They were more or less involved in late Silurian subduction. A part of these subducted series were sliced, exhumed and partially melted during middle Devonian.

- Arc and back-arc series and nappe-stacking of late Devonian to early Carboniferous points the slab dynamics, as the widespread magmatism (from mantellic and crustal origin) which occurred between Tournaisian to early Permian. Visean and its large felsic volcanic basins (which are very similar to the Taupo rift in New Zealand) and Stephano-Permian are particularly 'hot' and active periods for the FMC. They match with large mass and heat transfer as we can found in numerous convergent zone (especially Mediterranean and peri-pacific zones). The current lithospheric architecture of the FMC mainly results from this period.
- After Permian, Atlantic and Alpine Tethys opening as well as Pyrenean lithosphere break-off reactivate numerous faults, and cause mass transfer and fluids circulations (with F and Ba bearing-veins). Late Cretaceous to present shortening occurred in Pyrenean and Alpine belts, whereas Oligocene extension occurred along the West European Rift. During these Cenozoic times, the FMC has undergone little shortening during upper Cretaceous to Oligocene, a significant thinning in its north-eastern part during Oligocene and a scatter volcanism during Miocene. During late Miocene, volcanism became significant and a bulging uplift during Pliocene (200/300m at least) is documented.

Nowadays, there is a significant micro-seismic activity along the South Armorican Shear Zone up to the Sillon Houiller fault zone and along the N3° meridian around which magmatism mainly occurred (from South to North: Languedoc (1,9-<1Ma), Escandorgue (2,5-1,5), Causse (14-6Ma), Aubrac (8,7-6Ma), Cantal (13-2Ma), Cézallier (5,4-3Ma), Sancy (1-0,2Ma), Mont-Dore (3-1,5Ma), Limagne (54-12, 3, 1,2-0,09Ma), Chaîne des Puys (0,156-0,007Ma), Chaîne de la Sioule (15-2Ma). Moreover, the N3° meridian separates different surface movements characterized by GPS signal treatment (Tesauro et al. 2005) involving a left-lateral strike-slip motion along this zone. Below this limit, a thin lithosphere (50-60km) is assumed (Sobolev et al. 1997). The recorded maximum and minimum horizontal shortenings are respectively oriented NW-SE and NE-SW. They are consistent with the regional signal and compatible with the left lateral strike-slip motion. The maximum main stress direction is vertical or horizontal and the minimum main stress direction is horizontal (exceptionally vertical) (ie extension and strike-slip are the main kind of regime).

Bulging uplift, magmatism, bouguer anomaly, thin (and light) crust, thin lithosphere and high topography support for upward flows of asthenosphere and/or lithospheric heat anomalies, geological time span processes. Therefore, the FMC seems to have an important heat potential.

3.2 Qualification of the resource

The Sioule license is located between two lithospheric-scale fault zones (Sillon-Houiller (and Aigueperse-St-Sauve (ASSFZ)). It is mainly composed of lower Carboniferous granites, volcano-sedimentary series ('tufs anthracifère') and Devonian (to Tournaisian ?) metamorphic rocks (migmatites, paragneiss, orthogneiss, micaschists) (Figure 2). These lithologies are covered by (1) the Oligocene basin of Olby (along the ASSFZ) whose thickness is lower than 400m, (2) the Pliocene volcano-sedimentary series of the Mont-Dore and (3) the Pleisto-Holocene volcanic series of the Chaîne des Puys (CdP) with a thickness lower than 200/400m.

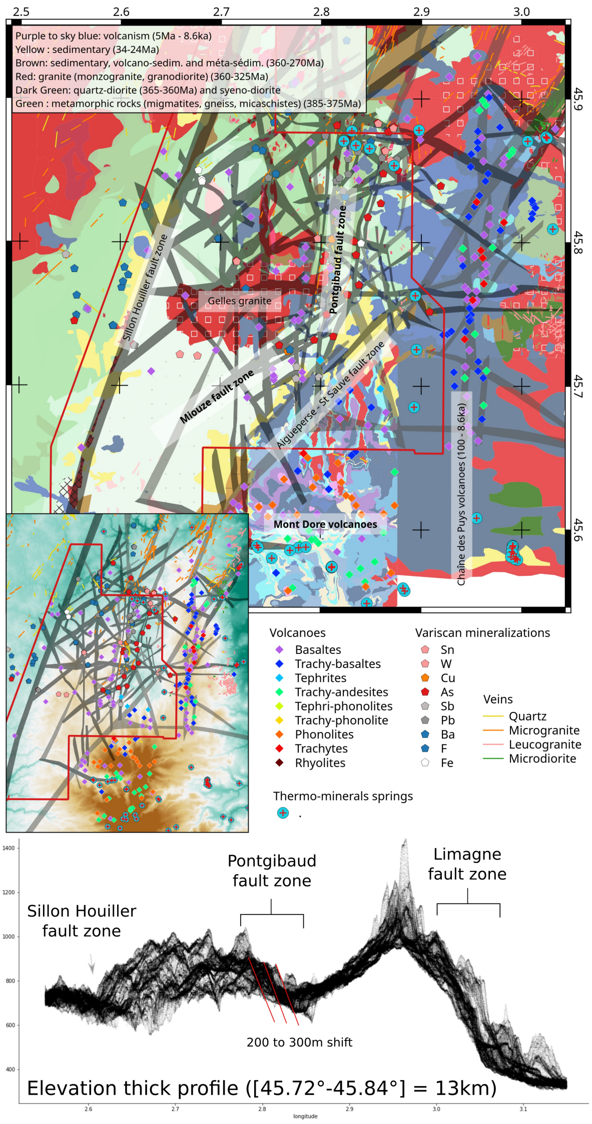

Figure 2: Geological map of the Sioule license.

Drain. The main targeted drain is the Pontgibaud fault zone (PFZ). This N-S fault zone was active during the Gelles granite emplacement (probably during Visean). Tourmaline is observed in pockets within granite, shear bands and brittle fault/veins and underlines the fast transition between magmatic state and brittle deformation. Thin mylonite to ultramylonite bands, with a dip toward the SE and with top-to-the-SE kinematics, are observed close to the granite/metamorphic interface. These structures were cross-cutted by brittle normal faults with a dip toward SE and with top-to-the-SE kinematics (Bellanger et al., 2017). These last structures are associated to steep veins which host W-As-Au-Bi-Sn (>400-350°C), Sb-Sn-Zn-Pb-Ag (350-200°C) and Zn-Pb-Ba-F (<200°C) mineralizations. The two higher temperature sets of mineralizations are probably related to the Gelles granite emplacement and cooling whereas the later reflects remobilization during Stephano-Permian and early Jurassic events. All of these criteria indicate that the Gelles granite was emplaced as a Core Complex and that the PFZ has a crustal-scale size and has been reactivated and was intersected by other faults several times (Figure 2, Figure 3). The PFZ is associated to a recent 300m shift of the topography (also underlined by the regolith profile) over 15km length along N-S trend, parallel to the CdP volcanoes (Figure 2). This shift could be Oligocene, Pliocene (3-2,5Ma) but it is more probably Pleistocene to Holocene (synchronous of the CdP magmatic events). Analysis of 14 seismic focal mechanisms over the license indicates that the fault-planes that currently slip are N-S to WNW-ESE. It is consistent with the slip tendency analysis using extrapolated stress profiles of Chassoles (Figure 3). Therefore, the fault zones which have N-S and WNW-ESE orientations have higher probabilities to be permeable (Barton et al., 1995).

Fluids. Structural analysis suggests that the PFZ is permeable up to a great depth. Thermo-mineral springs, CO_2 soil-flows and 3D-magnetotelluric models also sustain this hypothesis. Indeed, there are seven thermo-mineral spring clusters to the East of the Sioule license (Table 1), mainly scattered along the main fault zones (Figure 4). Thermo-mineral springs temperatures vary from air temperature to 56°C and geothermometers suggest that these fluids have undergone fluids-rocks interaction temperatures between 110 and 240°C at least (Table 1). Moreover, mantellic gases (CO_2, He) highlight brittle crust permeabilities between surface and magma storage (at least) (Bräeur et al. 2017). Mapped CO_2 soil flows and available data over the biological emissions (Bond-Lamberty and Thomson 2010) indicate that the Miouze-Pontgibaud fault intersection is permeable to mantle-sourced carbon dioxide. Finally, magnetotelluric models indicate that there is a conductivity anomaly within the Miouze-Pontgibaud fault intersection. If the shape of this anomaly varies with models, its location remains within the fault intersection and its geometry remains connected to a deeper anomaly, below 10km depth (Figure 5).

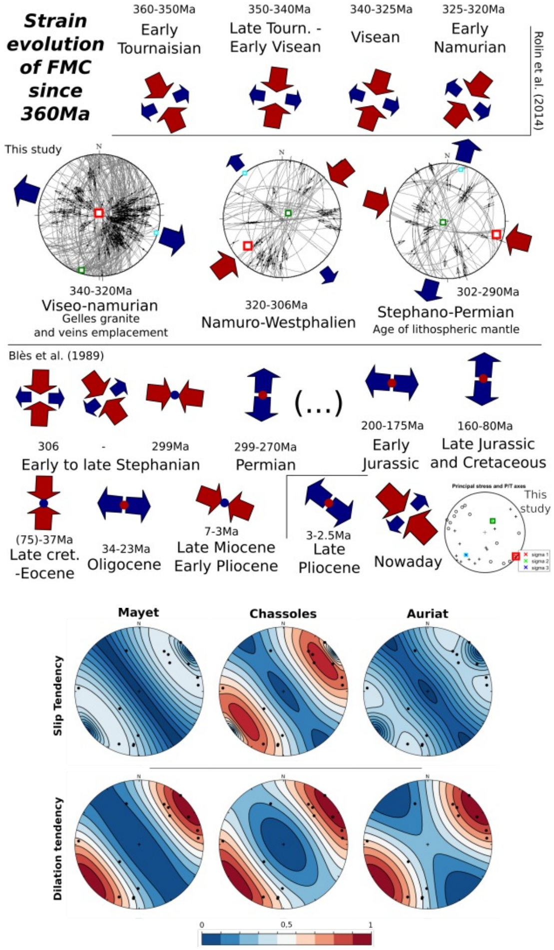

Figure 3: **Evolution of strain and stress axes since 360Ma. Stereo come from our structural data inverted using T-TECTO, from our seismic focal mechanism inversions and from slip and dilation tendency analysis using three extrapolated stress profile from wells data (Cornet and Burlet 1992) at 3km depth. On these last stereos black dot are pole of fault-plane that slipped after seismic focal mechanism analysis of 14 micro-earthquake occurring between 12/2015 and 08/2016. Other data come from Blès et al. (1989), Rolin et al. (2014), Heidbach et al. (2016).**

Table 1: **Springs cluster properties. 1: Aiguerperse-Saint Sauve FZ, 2: Pontgibaud FZ, 3: Sancy-Mont Dore caldeira, 4: Saint Nectaire, 5: Limagne FZ, 6: South Limagne FZ, 7: Limagne basin. SiO2: Fournier (1977) law for quartz without steam loss, NaKCa: Fournier & Trusdell (1983) law, NaLi: Michard (1990) law (established from fluids in european granite settings).**

	Fault Z. azimuth.	T (°C)	Q ($L.s^{-1}$)	T (°C) SiO2	T (°C) NaKCa	T (°C) NaLi
1	NE-SW	9,5-42,3	0,09-120	124±28	146±35	213±18
2	N-S	10-37	0,6-4	151±23	115±7	199
3	-	5,7-56	0,06-15	150±19	151±27	148±48
4	-	9,9-36	0,2-5,3	143±23	161±31	236±4
5	N-S	8,5-33,9	0,8-90	131±14	145±25	217±28
6	NW-SE	12,8-14,7	3,6	117±13	177±12	198±8
7		13,4-22,7	0,27-0,72	108±15	159±23	193±43

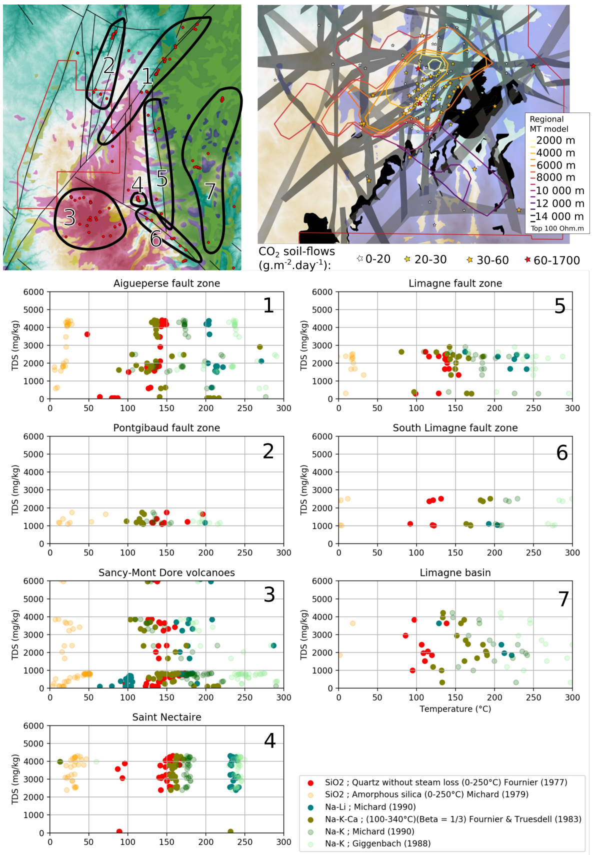

Figure 4: Thermo-minerals springs (red dot) groups and geothermometry results (versus TDS, expressed without O and H weight). Upper right: CO2 soil-flows, fault network and brittle-crust MT anomaly shape from MR2018 MT model.

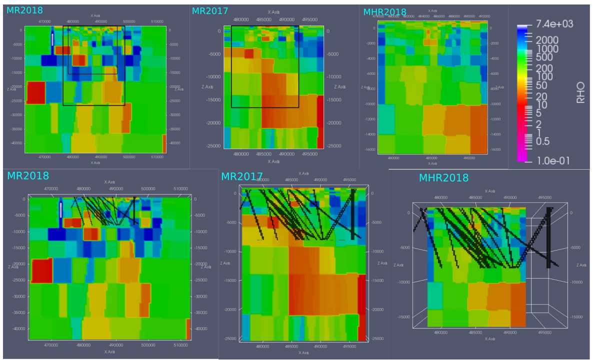

Figure 5: E-W cross-section from MT models performed by IMAGIR (Regional model MR2017 and MR2018 and High resolution model MRH2018).

Heat.

Heat sources, heat anomalies and quick heat transfers in the studied area mainly result from: (1) aqueous fluids convection within the brittle part of the CFZ, (2) magmatic fluids dynamics from mantle to BDTZ, (3) high radiogenic heat production and maybe (4) asthenospheric friction (if asthenospheric flows occur).

The temperatures at 30km depth have been constrained from mantellic thermal models (independent to surface heat measurements) between 750 and 850°C by Sobolev et al. (1997). In addition, heat flows from mantle has been constrained at Moho depth (30km) between 25 and 40 mW.m^{-2} using the previous thermal model and heat conductivity from 3 to 3.5 W.m^{-2}.K^{-1} (Figure 8). The average radiogenic heat production from FMC granite and metamorphic rocks are respectively close to 4 and 2 µW.m^{-3}.

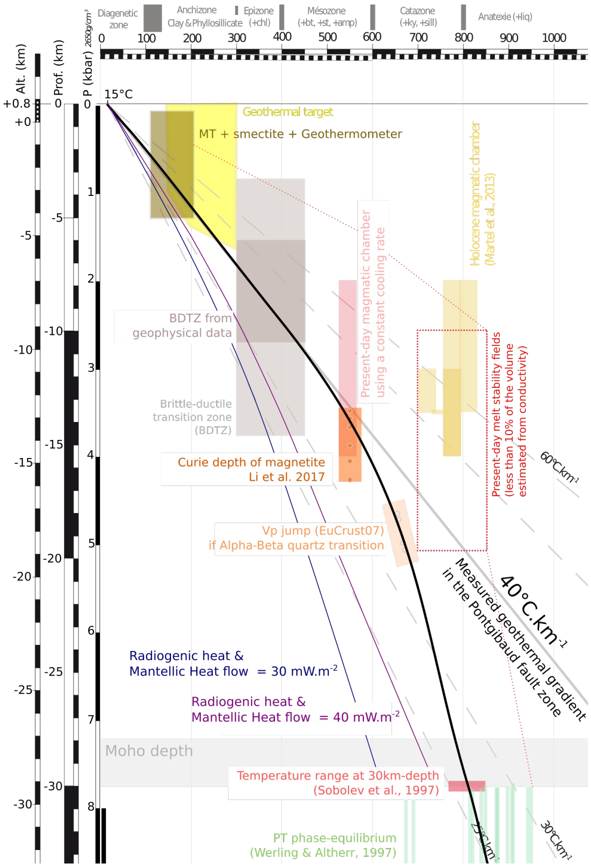

Figure 6: Regional pressure-temperature range for the Sioule license, build from nine independent datasets.

Knowledge over trachyte petrologies suggests that these magmas were emitted between 15ka and 9.2ka from a cooling magmatic source (from 810 to 720°C) located between 3.5 and 2.75 kbar (10-14km depth) (Martel et al. 2013). The four older volcanoes of the CdP (Clierzou, Grand Sarcouy, Puy de Dôme, Chopine) have a good correlation ($R^2 = 0.9896$) of their age (15, 13, 11 and 9.7ka) with their temperature before emission (810, 775, 750, 720°C). If we linearly extrapolate this cooling rate (16°C/ka) we obtain a current temperature of 565°C at around 12km depth. This is consistent with the Curie depth of magnetite (550°C) estimated between 13.5 and 16.5km depth by Li et al. (2017). Moreover, as suggested by thermodynamic approach (Abers and Hacker, 2016), we can consider that the major Vp jump modeled by Tesauro et al. (2008) (EuCrust07) is related to alpha to beta quartz transition. Therefore, we can use this interface as an isotherm and we obtain three independent data giving consistent results (Figure 6).

Moreover, our geophysical joint inversion (electrical resistivity - shear waves velocity - density) suggests a BDTZ between 6 and 10km depth (Ars et al. 2019). An electrical resistivity anomaly between 1 and 5km depth could represent smectite, with temperature stability fields between 110 and 200°C as suggested by geothermometers (Figure 6). It is continuously connected to a deeper anomaly at 10km depth which could represent a distributed small fraction of melt around 700 to 800°C (see Laumonier et al. 2017). A geothermal gradient well supports the hot thermal state of the crust beneath the Sioule license with a measured value of 41°C.km^{-1} within the Pontgibaud fault zone (Global Heat Flow Database, datapages.com).

Finally, integration of all these data into a numerical model demonstrates that convection is able to generate heat anomalies of 150°C at 2.5km depth, even if the regional temperature at 5km depth is 150°C (Duwiquet et al. 2019).

4. DISCUSSION & CONCLUSION

Crustal fault zones are one of the most promising features for holding geothermal resources, with or without active magmatism. The Pontgibaud fault zone is one of these CFZ. Located in a felsic crust (granite, gneiss...) with deep and scarce melt evidence (>10km depth, <<10% of melt), the PFZ shows evidences of permeability from surface to BDTZ. A drilling in the next few years will allow for demonstrating the ability of CFZ to generate an important geothermal resource. If this drilling is a success, we plan to demonstrate the ability of CFZ to generate geothermal resources even without any evidence of magmatism in the Combrailles-en-Marche license, located 55km to the NW of the Sioule license.

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