European Geothermal Congress 2016

Strasbourg, France, 19-24 Sept 2016

The Key role of first-order geological paradigm in deep geothermal exploration.

Mathieu Bellanger[1], Jean-Luc Auxiètre[1], Jean-Michel Ars[1, 2], Sophie Hautot[3], Pascal Tarits[2].

[1] TLS Geothermics, 14 bis chemin de l'Enguille, 31180 St Geniès-Bellevue

[2] IUEM, UMR Laboratoire Domaines Océaniques, 29280 Plouzané, France

[3] IMAGIR Sarl, 29200 Brest, France

mathieu.bellanger@tls-geothermics.fr

Keywords: geological paradigm, deep geothermal exploration.

ABSTRACT

The approach of TLS-Geothermics for deep geothermal exploration is based on two axes of research. The first one, which is also the first step, is the development of the first-order geological knowledge (developed here). The second one concerns technological development for local physicochemical characterisation (static to dynamic) in three dimensions and involves a geological model coupled to geophysical measurements and numerical modelling. These axes are presently tested on two high temperature projects supported by TLS Geothermics in the French Massif Central.

TLS Geothermics defines the intrinsic problematic of deep geothermal exploration as **targeting a natural drain where circulate hot fluids**. To solve this, it appears essential to combine its induced problematics. The result of this approach is that **first-order geological paradigm is a key parameter to improve a solution which leads to drastically reduce the geological and drilling risks**.

As the deep evolutions of the crystalline structures are poorly constrained due to a lack of deep well in this geological environment (typically deeper than 0.5 to 1km), it results that various paradigms can explain the geodynamic evolution of the Variscan belt. These paradigms involve highly contrasted features at depth, features which have first-order controls on the physicochemical properties of the drains and reservoirs, in terms of ability for the fluid flows and heat transfers. Actual paradigms about the Variscan dynamic of magmatism perfectly illustrates this purpose. The first paradigm involves a plutonic emplacement as a 'bubble' of granitic melt which moves upward into the ductile crust (diapiric intrusion) and which is stopped to the base of the brittle crust under which it can be spread to form a laccolith. The melt could also join the surface using newly formed or inherited faults and fractures of the brittle crust. This dynamic leads to drawn the magmatic bodies as isolated within the nappe stack. Another paradigm, less common in literature, involve the plutonic emplacement as the model of Core Complex. This last one is argued here. We demonstrate how it has a significant impact on crustal cross-sections and so on the crustal interfaces (structural and rheological) which could drive fluids flow and heat transfers. The drastic differences in the crustal conception which use various geological paradigm (but similar data), do of this one a first-order key parameter to constraint crustal fluids flow and heat transfers, critical for the deep geothermal purpose.

1. CONTEXT AND CHALLENGES

Although the earth calories were exploited to produce electricity since the first decade of the XXth century (Larderello, Italy), the geological concepts for exploration stage remain unstable, with -for example- a lifetime of about 5 to 20 years in the Upper Rhine Graben (Vidal et al., 2015). **The geothermal concepts remain unstable** (Fig. 1).

A bad geological concept often leads up to a failed prospect, as the one of the Bac de Montmeyre in the 70's (Puys de Dôme, France), where the target was a hypothetical superficial magmatic chamber. Such **failure often leads to a considerable increasing of the delay** for the geothermal resource exploration and can generate distrust of the population (and investors) with respect to the geothermal energy.

A high resolution geological model, argued during the first exploration stage, is essential prior to any drilling. This model needs to solve the following problematic: **Target a natural drain where circulated hot fluids**. However, due to the lack of knowledge about the deep

crustal structures and fluids flow as well as to the punctual outcroppings of rocks on the topographic surface, the models are often highly interpretative and this simple problematic **is complex to solve**.

One of the innovative objective proposed by TLS Geothermics for the geothermal exploration phase is to highly **increase the degree of accuracy** of the geological model -from crustal (at least) to thin-section scale- using an intensive **field working** and researches about the **geodynamical history** of the studied system.

The geothermal concept used by TLS Geothermics are brittle fault zones rooted in the ductile crust (crustal scale fault zone). These ones are supposed to favour upward driving of large amount of fluids and calories (Fig. 1).

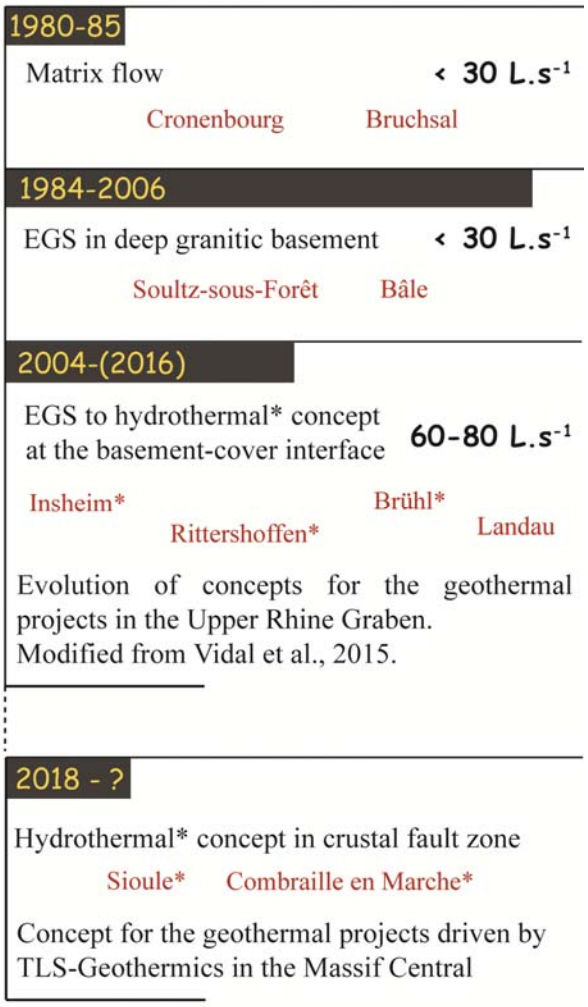

Figure 1: A French example of the recent evolution of concept for geothermal projects. The grey bars represent their respective lifetime.

2. GEOLOGICAL PARADIGM: EXAMPLE FROM INTERPRETATIONS OF CRUSTAL STRUCTURES OF THE FRENCH MASSIF CENTRAL

The classical key parameters analysed during the exploration phases often concern local drains (Mazurek, 2000), reachable to human observation (Fig. 2). The knowledge of these parameters remains essential. However, the scale changes can make null and void some of these parameters. To the crustal scale, these ones can be qualified using a geodynamical theory. The models from these theories can significantly modify the characteristics of the key parameters as the pre-existing geometry, the host rock lithology, the mechanism of deformation…

To illustrate this purpose, two contrasted (but recent) crustal cross-sections for the eastern Massif Central are presented (simplified and harmonized) (Vanderhaeghe and Teyssier, 2001; Faure et al., 2009). If authors have used the same geological data from surface, the interpretation in depth is highly contrasted (Fig. 2) especially because they have chosen two distinct geological paradigms to explain emplacement of the plutonic bodies.

Following the first interpretation (Fig. 2) (Faure et al., 2009), the major fault zones are flat and correspond to the Fameno-Tournesian nappe stacking. In Cévennes (south of the cross-section), granitic bodies correspond to ‘bubbles’ (diapiric intrusion) typically intruded in a ductile layer. Finally, the crust below 10km of depth is supposed to be a proterozoïc basement, an assumption from the geodynamical paradigm used by the authors to construct the cross-section.

Following the second interpretation (Fig. 2) (Vanderhaeghe and Teyssier, 2001), the major fault zones have a steeply dipping and are connected to a flat detachment which corresponds to the top of the Core Complex units. This paradigm implies that the granitic bodies are connected to the lower crust units.

If these two models, based on two different paradigms, are consistent with the first-order data from surface, it’s clear that they haven’t the same implication for the first-order evolution of structures (i.e. potential drain) in depth at crustal scale.

Due to the drilling depth required by the deep geothermal purpose, the targeted drain or reservoir have necessarily a crustal scale. Thus, the first-order geological paradigm is a key parameter to improve a solution which leads to drastically reduce the drilling risk. The geological paradigms can be discussed using a geodynamical history consistent with the field and geophysical results.

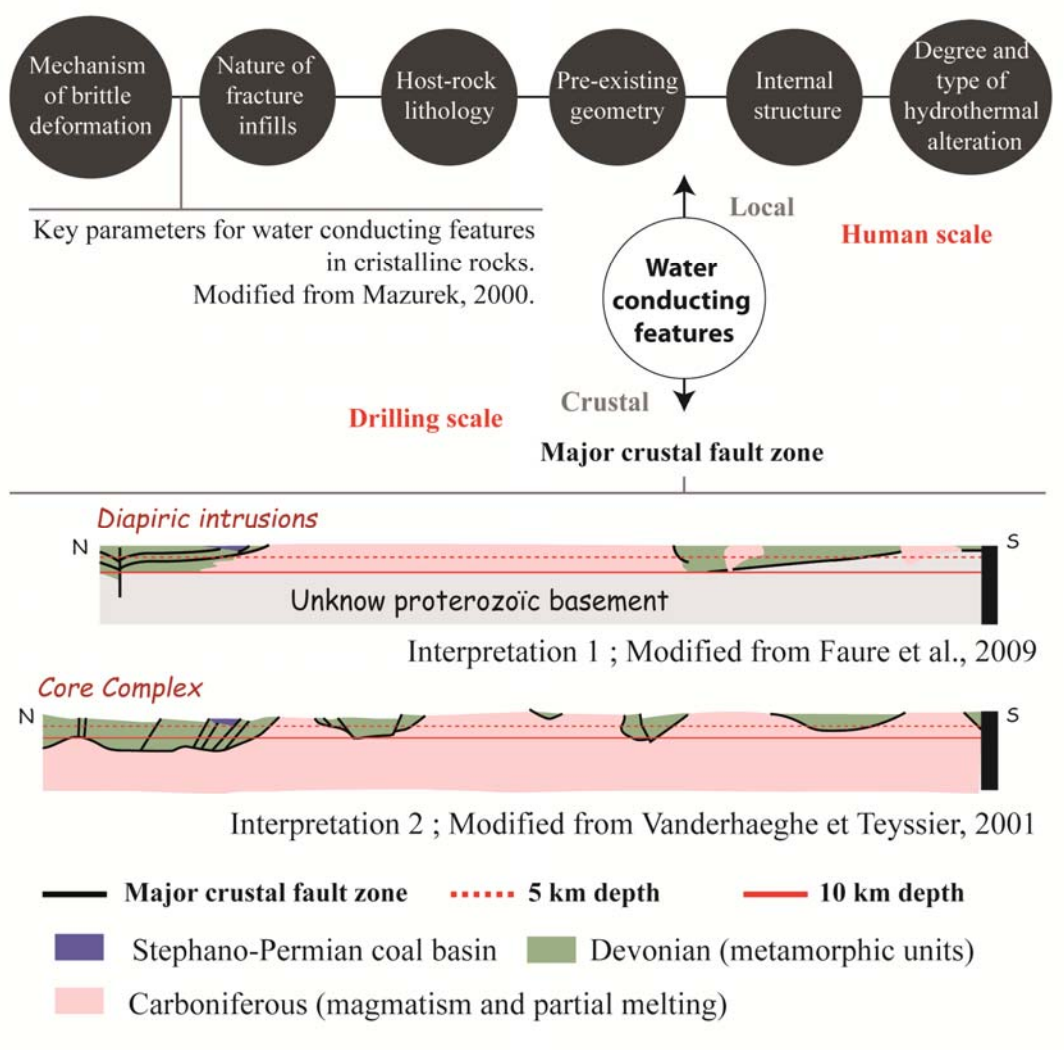

Figure 2: Key parameters for water conducting features from local/human to crustal/drilling scale in crystalline rocks. The key parameters at crustal scale highly depend of the selected geological paradigm. These paradigms can be discussed using the knowledge of geodynamical process. For example, two crustal cross sections (the thick black bars represent a depth of 30km) of the SE Massif Central are presented. They were drawn using two geological paradigms (diapiric intrusions versus core complex for the Variscan magmatism emplacement).

3. A DEMONSTRATOR

3.1 The targeted drain

To argue our strategy, TLS Geothermics requested an exclusive exploration licence in the West of the volcanic structure of the Chaîne des Puys (Puys de Dôme, France).

In this area, a large mineralized fault system (30km of length at least) has produced great amount of lead (50.10^6kg) and silver (1.10^5kg) during the XIXth century (70km of galleries up to 150m in depth).

- ***An inherited drain***. This system is characterized by high content of arsenic which underline, with mineralisation and hydrothermal alterations, significant late-magmatic fluids circulation in the fault system (Fig. 3).

- ***A drain able to drive magma ascent***. The Petite Chaîne des Puys, composed by Pleistocene to Holocene basaltic volcanoes, were formed after that the magma has drived in this fault system. The NS trend of the Chaîne des Puys suggests the eastern continuity of this fault system.

- ***A current drain***. Current fluids circulation is attested by the CO_2 rich thermominerals springs of Barbecot, Pranal and Châteauneuf-les-bains (further north) as well as by a high heat flux of 120 mW.m^{-2} (the regional heat flow is close to 80 mW.m^{-2}).

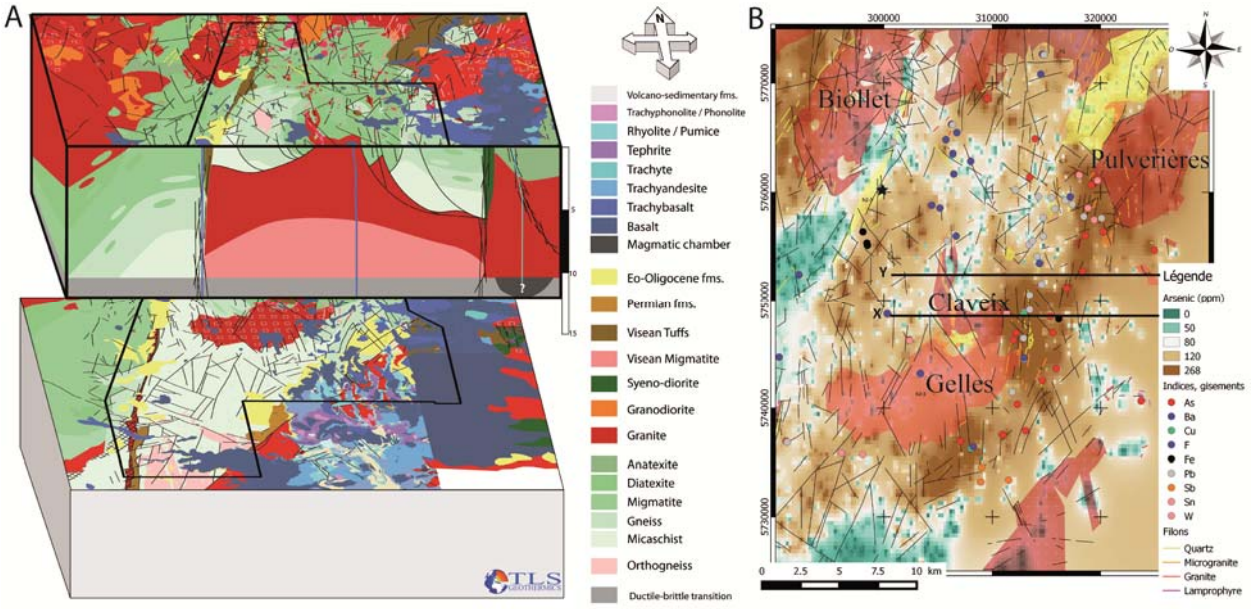

Figure 3: A. Geological model for the Gelles massif using the Core Complex paradigm. After Ars et al. (2015). B. Arsenic content (ppm) in soil and sediment, carboniferous (mainly visean) magmatic formation (red: granite; orange: microgranite; yellow: tufs) and ore deposits. The cross-section X and Y refer to the figure 5.

Whereas the subsurface geometries of the fault system are well constrained by the numerous ore mining galleries, evolution of these ones at depth remains hypothetical. We now demonstrate how considering the geodynamical history of a crustal-scale system can increases depth accuracy of the geological model around a targeted drain.

3.2 From a geological paradigm to a local faults system

- ***Regional paradigms***. The main geological paradigm for the crustal cross-sections of the French Massif Central corresponds to an important nappe-stacking cross-cutting by diapiric intrusions (e.g. Matte, 1986; 1991; Faure et al., 2009). If there are many variations in the geodynamical models (compression/extension/ transcurrent partitioning; Himalayan mountain type; Basin and Range mountain type; role of the subduction; role of thickening and magmatic underplating for the melting of the lower crust; spatial and timing extension of events…), all of the cross-sections which have used this paradigm have drawn a crust mainly composed by the nappe-stacking and have rapidly ended the continuity of magmatic bodies in depth. However, several facts do not support this paradigm and argue for a similar geodynamical context than the Aegean Sea (i.e. core complex emplacement resulting of high extension due to slab retreat within a convergent plate system). Following this paradigm, plutonic bodies are the top of Core Complex doming (Fig. 2).

- ***Local implications***. Following this paradigm, the Pontgibaud fault system was initiated in an extensional context (and not transpressional) during the middle visean and would belong to a flat detachment which has accommodated large amount of displacement. This paradigm supposed (1) that the metamorphic series are not around the granite but are affected by boudinage above the granite, (2) that the Pontgibaud faults system slightly plunges toward the east at depth (Fig. 3A) and (3) that the deformation are mainly normal faults or detachments.

- ***Local observations***. Despite the limited field outcrops, we have observed several extensional structures from ductile-brittle to brittle behaviour consistent with this model (Fig. 4). The many NNE-SSW brittle extensional faults and tension gashes (filled by microgranites or by late-magmatic mineralization) observed in the Devonian metamorphic rocks testify to the extension underwent by these series during the magmatic activity. Moreover, the middle visean volcanic emissions (tufs anthracifères) are spatially close to the middle visean granite and attest to the rapid ascent of the granitic bodies. This rapid ascent cannot be realised within the brittle crust and is thus irreconcilable with a thick brittle crust during the middle visean times at least (under the sea level everywhere in the French Massif Central). This observation highlights the thinness of the upper crust during the magmatic activity, which is easily explained with the Core Complex paradigm.

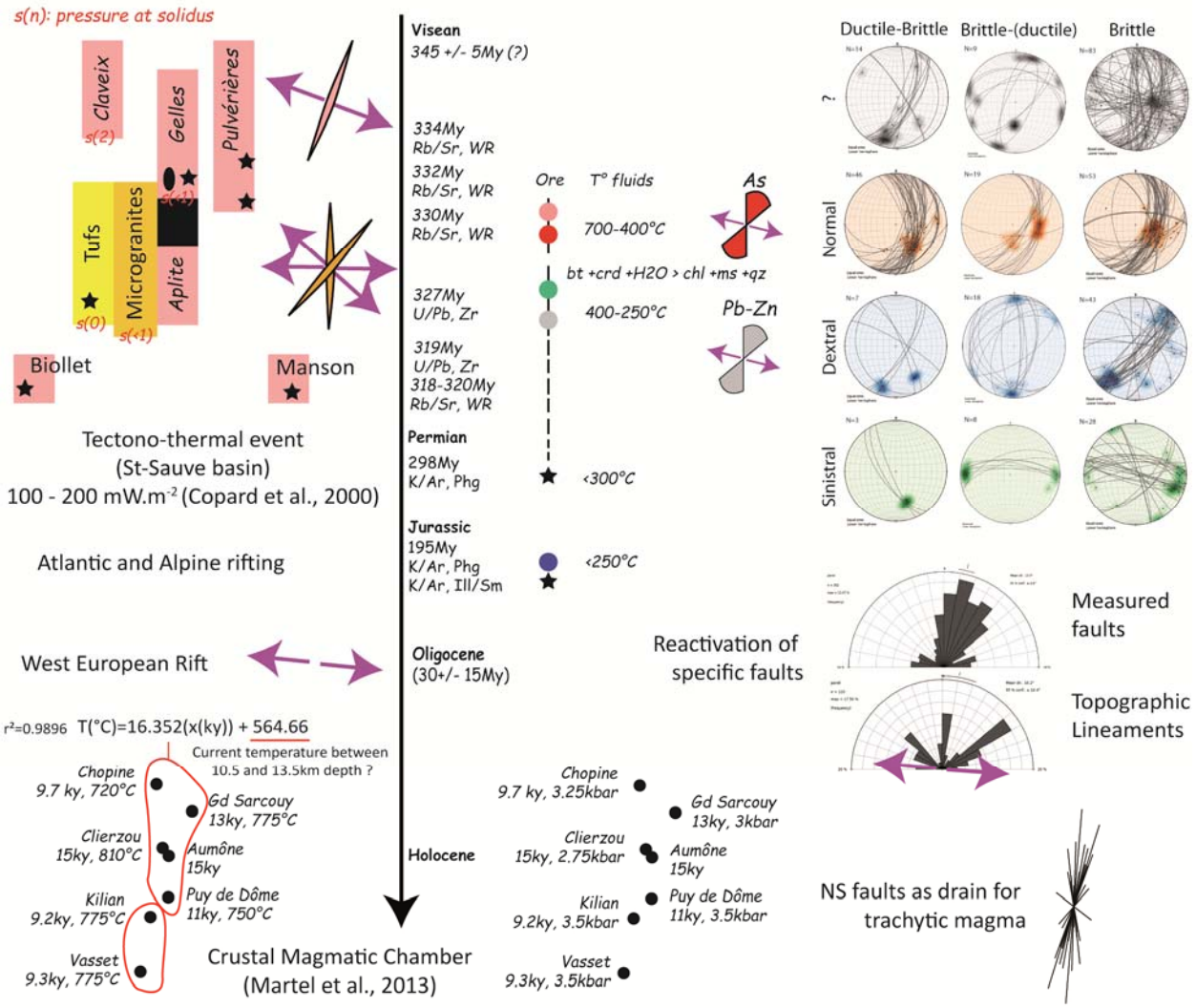

Figure 4: History of the Pontgibaud fault system since Visean. The syn-magmatic Visean Pontgibaud fault system is mainly NNE-SSW and was reactivated during each following geodynamical event.

3.3 Consistency between geological and geophysical models

- ***Geophysical and geological models***. A magnetotelluric (MT) campaign (see Ars et al., 2015 for details) was conducted over the studied area, at the autumn 2015. A 3D inversion was realized -without any geological consideration- by IMAGIR (a worldwide recognized expert). The results of this raw MT model (22x22x22km) are in accordance with the initial geological model based on the Core Complex paradigm and drawn in springtime 2015 (Fig. 5).

- ***Key features for consistency***.

(1) The granitic/migmatitic Visean rocks correspond to the highest resistivity values (>1000Ωm). This is coherent with the fresh facies of this unit observed in surface (except close to the border of the granitic body).

(2) The devonian migmatite correspond to intermediate resistivity values (500 - 1000Ωm). This is coherent with the strong alteration of this unit observed in surface (due to deformation and hydrothermal circulation).

(3) Assuming that these surface correlations are representative at depth, the geometries of the interfaces between the intermediate and high resistivity zone from the MT model is similar to the interfaces between the visean granite and the devonian migmatite from the geological model (Fig. 5).

(4) The expected magmatic chamber at the base of the brittle crust is coherent with an intermediate resistivity zone (200 - 500Ωm) staggered below 8km and above 14 km of depth. This zone is topped by a conductive zone (100 - 200Ωm) which could correspond to current hydrothermal circulations induced by a hot magmatic chamber (Fig. 4).

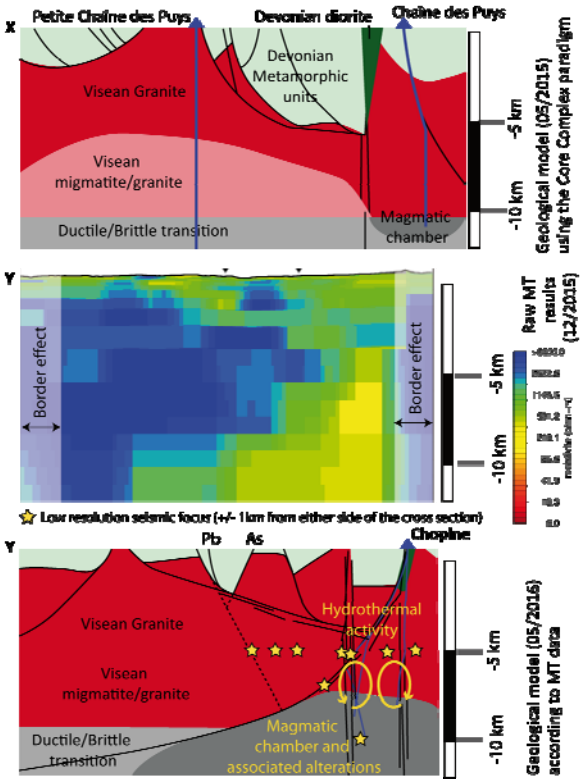

Figure 5: X and Y refers to the cross-sections localised on the figure 3B. X: cross-section drawn in springtime 2015 using the Core Complex paradigm. Y (top): cross-section in a 3D resistivity model from a MT inversion without any geological considerations. Y (bottom): the corresponding geological cross-section from geological mapping and MT results. Seismic focuses are from RENASS and EIDA databases.

If there are some differences between the MT and geological models, they are minor and do not affect the first order geometries. This consistency, between the forecasted geological model and the observed data (Fig. 5), sustains the paradigm involved and the applied strategy.

3. CONCLUSIONS

- This study underlines the importance of considering the geological paradigms during the first steps of the exploration phase to construct a reliable geological model.

- The retained geological paradigms need to be discussed from field evidences.

- The geological paradigm cannot be discussed without considering for geodynamical evolution and processes.

- The geological paradigm allows to characterise the drain at the crustal-scale, which is the scale of the drilling.

- All data sustain that the visean magmatism emplacement in the studied area follows the Core Complex paradigm.

The next steps are the 3D geological modelling and the joint inversion of geophysical data using this 3D model to estimate physicochemical properties of drains and reservoirs.

REFERENCES

Ars, J-M., Tarits, P., Bellanger, M., Hautot, S., Coutant, O., Auxiètre, J-L., Maia, M.: Joint Inversion applied to deep geothermal exploration, *Poster of the Joint Inversions in Geophysics Workshop*, Barcelonnette, France, (2015).

Copard, Y., Disnar, J. R., Becq-Giraudon, J. F., & Boussafir, M.: Evidence and effects of fluid circulation on organic matter in intra-montane coalfields (Massif Central, France), *International Journal of Coal Geology,* **44(1),** (2000), 49-68.

Faure M., Lardeaux, J.M., Ledru, P.: A review of the pre-Permian geology of the Variscan French Massif Central, *Comptes Rendus Geosciences,* **341(2),** (2009), 202-213.

Martel, C., Champallier, R., Prouteau, G., Pichavant, M., Arbaret, L., Balcone-Boissard, H., ... & Scaillet, B.: Trachyte phase relations and implication for magma storage conditions in the Chaîne des Puys (French Massif Central), *Journal of Petrology,* **54(6),** (2013), 1071-1107.

Matte, P.: Tectonics and plate tectonics model for the Variscan belt of Europe, *Tectonophysics,* **126(2),** (1986), 329-374.

Matte, P.: Accretionary history and crustal evolution of the Variscan belt in Western Europe, *Tectonophysics,* **196(3),** (1991), 309-337.

Mazurek, M..: Geological and hydraulic properties of water conducting features in crystalline rocks, in: Hydrogeology of Crystalline rocks, Stober I. and Bucher K. (Ed.), 3-26, (2000).

Vanderhaeghe, O. and Teyssier, C.: Partial melting and flow of orogens, *Tectonophysics,* **342(3),** (2001), 451-472.

Vidal, J., Genter A., Schmittbuhl J., Whitechurch H., Baujard C., Dalmais E: Evolution of concepts for the geothermal projects in the Upper Rhine Graben., *Poster of the European Geothermal Workshop 2015*, Strasbourg, France, (2015).