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CHARACTERISATION OF THE STRUCTURAL CONTROL ON FLUID FLOW PATHS IN FRACTURED GRANITES

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ABSTRACT

The characterisation of fluid flow in fractured media is complex due to the fact that the access to the reservoirs is restricted to the boreholes, and the resolution of geophysical methods decreases with depth. In addition, the structures in a sedimentary cover of a granite mass targeted for geothermal exploitation reflect only a partial amount of the structures affecting the hot basement. In this respect, two fractured variscan granites have been selected to investigate the fluid flow paths; both of them are located within the European Cenozoic Rift System (ECRIS).

The first case study is the experimental geothermal site at Soultz-sous-Forêts (Rhine Graben). Borehole seismic data (VSP) have been used to map some generally permeable structures developed at the hectometre scale in the vicinity of the wells. The pattern of structures revealed by this way suggests a clear expression of the variscan inheritance rather than a faulting linked to the opening of the graben. The activation of some of these structures can be due to the current stress field controlled by the Alpine push, and explains the major hydraulic connections between the wells.

The second case study is a batholith outcropping in the Catalan Coastal Ranges, allowing a continuous structural analysis from centimetre to kilometre scales. A network of carbonate veins has been considered as a witness of past circulations. Both the extent and the conditions of precipitations of these carbonates allow to consider the outcrop as a fossil geothermal reservoir. The veins studied in this analogue outcrop and at Soultz-sous-Forêts allowed to identify different drainage patterns developed in a fractured granite. At the kilometre scale, the drainage may either be localised in the major structures, or be more homogeneously or randomly distributed, implying an important contribution of the protolithe.

INTRODUCTION

Drilling costs represent the major part of the total amount of a deep geothermal project *(Heidinger*, 2010). Thus, optimising the ratio between the length of the boreholes and their hydraulic and thermal performances is a key point to address for future development of deep geothermal energy *(Petty et al.*, 2009). Especially in the case of fractured reservoirs, clever locations and trajectories of boreholes can answer this need, for instance by intersecting as much permeable structures as possible *(Luthi*, 2005; *Schutter*, 2003). Nevertheless, this requires a good knowledge of the reservoir, facing some major problems:

- Surface geophysics allow to investigate the largest structures of a reservoir, but their restricted resolution prevent their efficiency at lower scales *(Al-Ali et al.*, 2009).
- Surface seismic reflection methods are not efficient to delineate dipping faults in crystalline basements, due to the lack of subhorizontal reflectors (for instance: sedimentary horizons) and due to the acquisition and processing parameters which are not adapted to such targets.
- Coring and borehole imaging provide local and non exhaustive structural data. Extrapolation of these small scale fractures at reservoir scale is tricky.

In view of this, we present our recent works in the characterisation of fluid pathways in fractured granites. The above-mentioned problems are addressed in two case studies, the Soultz-sous-Forêts geothermal site (Rhine Graben, France) and an analogue outcrop located in Tamariu (Catalan Coastal Ranges, Spain). These two sites are composed by fractured granites that are very similar due to their age (variscan origin) and their tectonic history (especially the opening of the European Cenozoic Rift System).

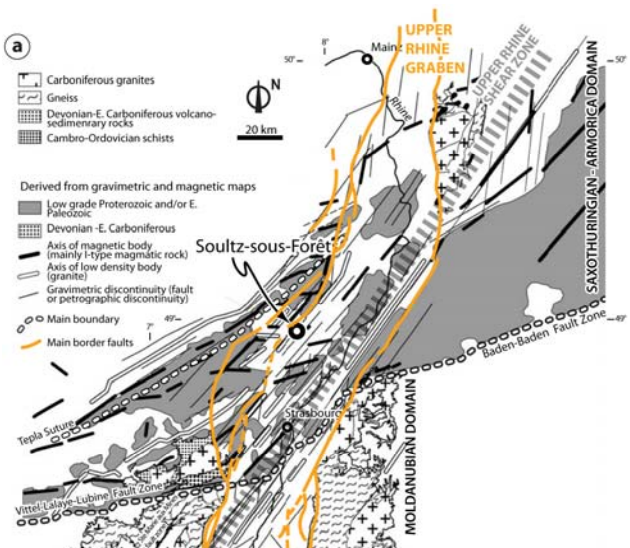
LIMITS TO THE CHARACTERISATION OF A FRACTURED RESERVOIR: THE SOULTZ-SOUS-FORÊTS EXAMPLE

In the framework of the industrial exploration of the Upper Rhine Graben (URG) for geothermal energy, an Enhanced Geothermal System (EGS) is being developed at Soultz-sous-Forêts since decades *(Gérard and Kappelmeyer*, 1987) (Fig. 1). At present time, three deep geothermal wells reach 5000 m depth in the Soultz-sous-Forêts basement and allow to access to temperature of 200°C *(Genter et al.*, 2010). A set of older and less deep wells is also available, like GPK1 and EPS1 which are studied later in this paper.

The boreholes reach the crystalline basement at a depth of about 1400 m, below a sedimentary cover deposited from Permian to Quaternary. The basement of the Rhine Graben area formed by the collision of large variscan domains *(Édel and Schulmann*, 2009; *Franke*, 2006). Major thrusts and suture zones trend NE-SW to ENE-WSW, such as the Vittel-Lalaye-Lubine-Baden-Baden fault zone and the Tepla Suture (Fig. 1).

The Soultz-sous-Forêts granites emplaced in Carboniferous times *(Cocherie et al.*, 2004) during the transition between collision and collapse tectonics of the variscan orogen. The collapse occurred until Permian times, forming basins trending NE-SW to ENE-WSW *(Ziegler et al.*, 2006). Large brittle and ductile strike-slip faults mainly oriented NNE-SSW to ENE-WSW and NW-SE were activated more or less contemporaneously with the development of these basins *(Arthaud and Matte*, 1975).

An other intensive deformation phase occurred in the Tertiary, with compression tectonics forming Alpine orogenes and extension developed through Europe (European Cenozoic Rift System) *(Bourgeois et al.*, 2007; *Dèzes et al.*, 2004; *Ziegler*, 1992). The formation of the Rhine Graben is attributed to a polyphased history, with a main E-W extension phase in Rupelian followed by transpressional and transtensional tectonics in Chattian and Miocene *(Schumacher*, 2002; *Villemin and Bergerat*, 1987).



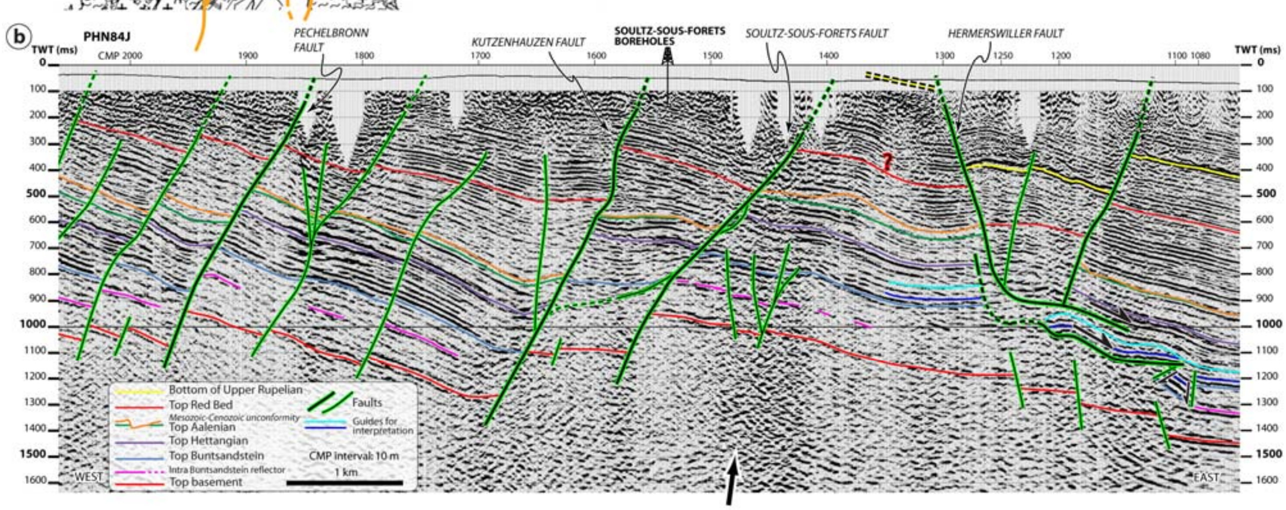


Figure 1: a) Position map of the Soultz-sous-Forêts EGS within the Upper Rhine Graben, illustrating variscan units and structures (modified after Édel and Schulmann (2009) and Édel et al. (2007)). b) E-W oriented reflection seismic profile, allowing to delineate much more structures in the sedimentary cover than in the crystalline basement. The arrow at the bottom of the profile indicates the position of a major fault zone indentified by other methods in the basement; the expression of this structure in reflection seismic is only a discreet flower-like structure in the sediments.

Major Oligocene normal faults controlling the deposition of sediments strike N-S to NNE-SSW (see orange traces in Fig. 1a and green traces in Fig. 1b). The NNE-SSW orientation of some fault segments suggest a reactivation of Paleozoic structures *(Édel et al.*, 2007; *Schumacher*, 2002, see Fig. 1).

Thus, from this introduction, one can observe that:

(1) As the sedimentary cover is younger than the basement, the fault network of the sedimentary cover is probably a subset of reactivated and newly formed structures of the underlying basement (Fig. 2). In addition, decollements such as represented in Fig. 2 may contribute to differentiate the structural networks of the basement and its cover (see the Hermerswiller fault in Fig. 1b for a field example). In other words, some important populations of faults within the basement may not affect the cover as long as they are not reactivated during or after the deposition of sediments.

(2) The sedimentary cover may be efficiently investigated with typical geophysical methods like reflection seismic (Fig. 1b). However, no structure can be clearly observed in the so-called 'seismic fog' of the underlying crystalline rocks (Fig. 1b). Other geophysical investigation like gravimetric and magnetic anomalies which produced Fig. 1a do not have a resolution fine enough to detect faults at the scale of the reservoir; only large trends may be delineated (*Édel et al.*, 2007).

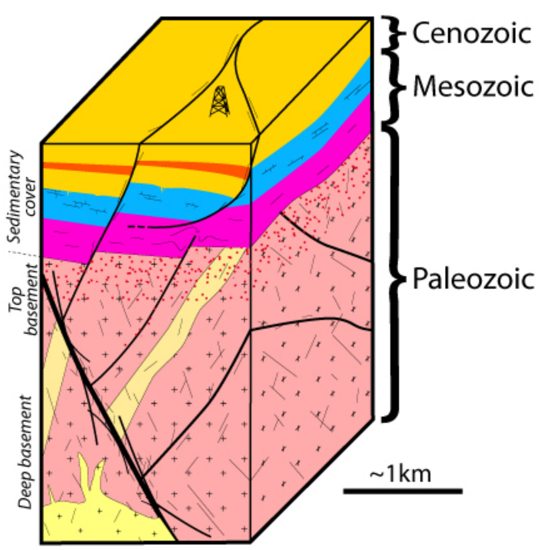


Figure 2: Structural model of an EGS site, based on the Soultz case study. The sketch illustrates that the faults patterns may vary depending on the age and the rheology of the formations.

These problems are added to the previous ones cited above. To address them, we worked in one hand in the direct investigation of structures by a **new seismic methodology applied to the Soultz-sous-Forêts site**, and in another hand, we tried to identify **general behaviours in the circulation of fluids** in fracture networks with the help of an **analogue massif**.

DIRECT INVESTIGATION OF A FRACTURED RESERVOIR BY UNCONVENTIONAL SEISMIC METHOD (VSP)

In the Soultz-sous-Forêts site, seismic reflection and conventional processing of walkaway and Vertical Seismic Profiling (VSP) have not been able to delineate steep structures *(Beauce et al.*, 1991; *Cautru*, 1989; *Dylikowski*, 1985, and see Fig. 1b). Even the contact between the sediments and the basement is discontinuously imaged. P and S wave velocities and hodograms have been used to track velocity variations and S-mode wave splitting; only a heterogeneity in the deep part of the GPK1 borehole has been detected, but without any orientation information *(Le Bégat et al.*, 1994).

Nevertheless, such borehole seismic data are acquired with a source at a fix surface position and sensors located in a well at successive depth levels *(Mari et al.*, 2003). By this way, seismic events such as reflections or refractions generated by structures that may present a high dip value can be recorded and analyzed for structural characterization. Last bu not least, thanks to the geometry of the equipment, VSP have the potential to bridge the scale gap between surface and boreholes methods (see the introduction and *Al-Ali et al.*, 2009; *Cosma et al.*, 2001; *Emsley et al.*, 2007; *Martí et al.*, 2006).

In this paper, we resume the processing, analysis and interpretation of a three-component (3C) VSP data set acquired at the Soultz-sous-Forêts EGS in 1993 in GPK1 and EPS1 wells. The aim is the 3D mapping of steep faults affecting the granitic basement at the geothermal reservoir scale.

After editing and formatting the data, the processing consisted in the upgoing and downgoing wave fields isotropic separation by a parametric separation routine. Then, an isotropic deconvolution of the upgoing wavefield was performed using an operator derived from the downgoing P-wave estimate. This method yields a better precision to discern the different waves especially when they arrive close together in time. Filters have been applied post separation and post deconvolution. Finally, the P wave direct arrival has been muted. This sequence has been applied to VSP’s acquired in GPK1 and EPS1 with P source positioned in four sites at the surface (Fig. 3b).

Fig. 3a presents an example of VSP after processing. Signals appearing more or less coherent through numerous depth levels are observed. They are interpreted as P-S conversions occurring on structures located laterally in the vicinity of the wells. When these reflections are partially blended with the P direct arrival, they occur on structures which are intersected by the well at the depth where the events arrive at the same time with the P direct arrival. In such a case, the intersected structures have presented high amount of gas and natural brine when drilled *(Aquilina et al.*, 2004), fluid outlets during hydraulic tests *(Evans et al.*, 2005; *Sausse et al.*, 2006), and tube waves when stimulated *(Jones*, 1993). Thus, one can consider at first order that these P-S reflections are a quite reliable signature of a permeable network. Thus, we developed a program to compute the position and orientation of each reflector expressed in the VSP data set. The computations consist in ray travel path and time modeling, which are iteratively compared to the observed travel times. Such a 3D computation is represented in Fig. 3b

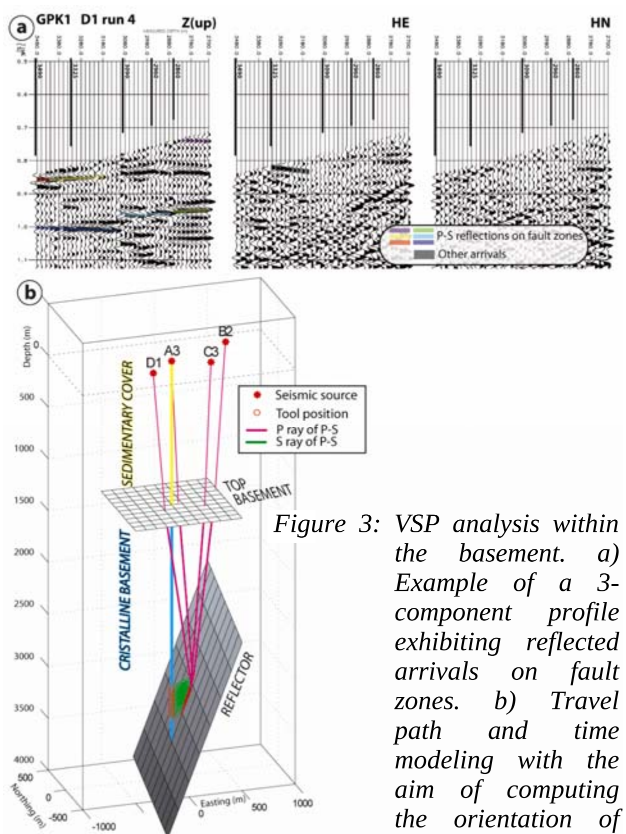


Figure 3: VSP analysis within the basement. a) Example of a 3-component profile exhibiting reflected arrivals on fault zones. b) Travel path and time modeling with the aim of computing the orientation of each reflector.

The resulting positions of reflectors are then introduced in the pre-existing reservoir model with the gOcad® software in order to improve the reservoir knowledge and propose a comprehensible 3D image (Fig. 4). This pre-existing static model is built on the basis of microseismic, VSP and televiewer data *(Sausse et al.*, 2010). A major fault called GPK3-FZ4770 previously described by these authors can be extended upward thanks to the new VSP results (Fig. 4a). A set of structures presenting several hectometres in extent is introduced as well (see the detailed view in Fig. 4b), probably connected to this major fault. On this basis, a conceptual connection plan is proposed in Fig. 4c. Structures that are represented by planes in the reservoir model (Figs. 4a&b) are presented by lines in the sketch, so that one can consider this sketch as a kind of vertical collapse of the reservoir model (with a loose of distance information). Then, results of hydraulic experiments and tracer tests are used to represent the hydraulic connections (light red color, Fig. 4c). Such a document is very useful for decisional aspects, like choosing production and injection boreholes, as it represents the major hydraulic connections between the boreholes.

The strikes of the structures are preserved in Fig. 4c. This obviously shows that the major flow paths occurring at the hectometre-kilometre scale are supported by structures oriented N025°E to N060°E, and N150°E. This first set of orientation (NNE-SSW to ENE-WSW) is typical of the variscan inheritance of the area (see introduction and Fig. 1a). The other orientation (N150°E) could be the signature of variscan events *(Ziegler*, 1986), but could also be a newly formed structure linked to Cenozoic tectonics (fault activated by transpression or transtension, as discussed by *Rotstein and Schaming* (2008)). N-S normal faults are not detected and, if any, do not seem to play a major role in the circulations.

These results lead to the following major conclusion: N-S faulting related to the Oligocene extension does not seem to have an important role in the present day fluid circulations. Likely variscan structures, which are thought to be reactivated at present time, represent some major fluid flow paths. Although N-S Oligocene structures are the most obvious features imaged by seismic reflection in the sedimentary cover (Figs. 1b & 4a), their control on fluid flow seems to be slight in the vicinity of the boreholes. In addition, the major fault zone (GPK3-FZ4770) presents a minimal extent of 4 km; it controls the major hydraulic connections of the boreholes. Nevertheless, it is very poorly expressed in the cover (Figs. 1b & 4a).

These results illustrate that specific methods especially devoted to the investigation of the basement are absolutely required for a good reservoir description. This fact has to be taken into account in exploration programs.

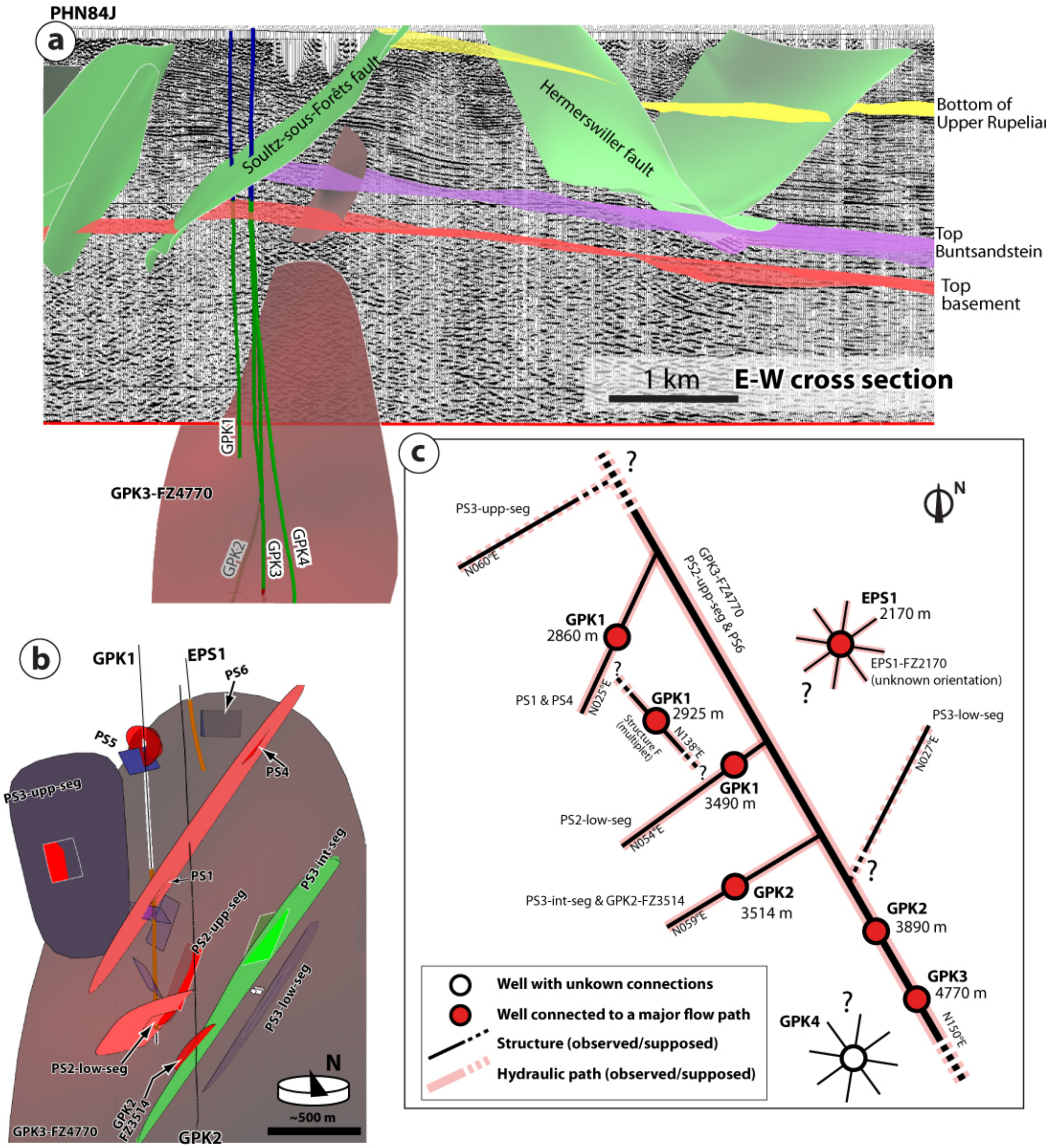


Figure 4: Representations of the Soultz reservoir model. a) -3D view- Some major normal faults of the sedimentary cover, and the major fault intersected by the boreholes within the basement. Note that this large structure is not well expressed in the sediments. b) -3D view- Detailed view of the structures identified in the basement. c) Conceptual sketch (2D map view) of the connections of the boreholes. Note that the strikes of the structures denote a variscan inheritance (Fig. 1) rather that the Oligocene E-W extension.

This first part of the paper deals with the structures occurring in the scale range of some decametres to some kilometres. In the following sections, we focus on complementary analyses of distribution of structures, continuously from the scale of the sample (centimetre) to the hectometre, along profiles of kilometric length.

STATISTICAL ANALYSIS OF THE CONTROL OF FLUID FLOW IN FRACTURED GRANITES.

Orientation distribution of the structures

In the Soultz-sous-Forêts site, we carried out some analysis of structural data gathered by *Genter* (1999) on the cores (~800 m cumulated length) of granite produced by the drilling of EPS1. Previous authors carried out some statistical analysis, sometimes by considering arbitrary sections of the boreholes *(Sausse et al.*, 1998). In this paper, we propose a simple analysis of the data as well, but we take into account the position of fault or altered zones described by *Genter* (1993).

The results in orientation are presented on Fig. 5c & d. The whole data set exhibits two main groups of orientations, grossly N-S trending and highly dipping (Fig. 5c). Some other groups may be distinguished, for instance with mean trends of N030°E or N135°E. A set of subhorizontal fractures can also be detected. If the structures occurring in fault zones or altered zones are excluded, the stereogram is grossly the same, except a relative decrease of the population which trends N-S and westward dipping (Fig. 5d). Nevertheless, the fractures oriented N040°E and dipping to the NW are still present, and even relatively more numerous (see arrow in Fig. 5d). This orientation is similar to one of the trends typical of variscan structures (see introduction and Fig. 1a, for instance the Upper Rhine Shear Zone). This similarity suggests that this population of fractures observed in EPS1 can be inherited from the early deformation of the granite in variscan times. It would be part of the 'primary fracture' defined by *Price and Cosgrove* (1990). This interpretation is strengthened by similar works in granites of Arabia *(Le Garzic*, 2010).

In addition, one can consider the veins filling the fractures as witnesses of past fluids circulations. We have thus chosen to sort the data in two groups, containing traces of calcite or quartz, in order to distinguish at least two likely different networks hydraulically active in old circulation phases. The stereograms of the two sets are very different (Fig. 5). Quartz veins trend mainly N-S or are subhorizontal (Fig. 5e&f), whereas carbonates trend N-S to NE-SW (Fig. 5a&b). Quartz veins are mainly found in fault zones *(Dezayes*, 1995) that is why only a few remains after excluding data from fault zones. These remaining fractures present generally low dip values, and are found at the top of the basement. Regarding the calcite data, when fault zones are not taken into account, the NE-SW orientation is slightly strengthened. It shows the important role of the primary fracturation in the circulation of the fluids having precipitated carbonates. Unfortunately, geochemical data (isotopes, dating…) lack about these carbonates. Thus it is not possible to know if the fluids circulated during the cooling of the pluton (that would be in agreement with the precipitation of carbonates). Nevertheless, to briefly conclude, our simple approach shows that different populations of fractures can be open and used for circulation during the history of the granite, depending on past strain fields.

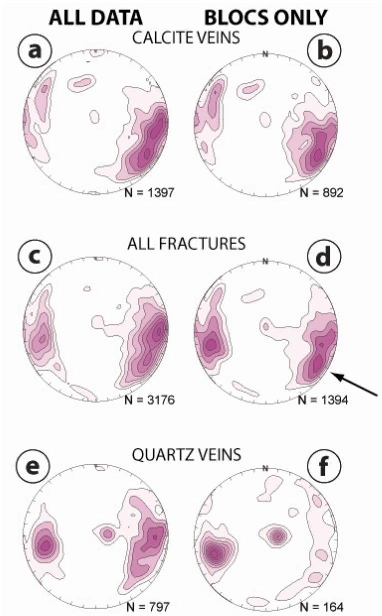


Figure 5: Stereograms of poles of fractures and selected veins observed in the EPS1 cores (lower hemisphere projection). Left: data considered all along the borehole. Right: data considered only in the fresh granite (data from fault and altered zones excluded).

Spacing distribution of the structures

The Soultz-sous-Forêts case study

Spacing distribution at Soultz-sous-Forêts have been analysed among other by *Genter et al.* (1997) (see *McCaffrey et al.* (2003) for a reference about the methods). In our study, we continue such analysis on the fracture networks containing quartz and calcite. The spacing values of the quartz veins follow a power law distribution in the 0.1m to 200 m range (Fig. 6a). This is the signature of non scale-dependent distributions *(Gillespie et al.*, 1993). Carbonate distributions are trickier to interpret. They follow a power law distribution locally in the 0.08-1 m and 0.1-70 m ranges (Fig. 6a). Nevertheless, these ranges are too narrow to consider the reliable identification of power laws. This fact could be interpreted as a signature of two different circulation phases in the past, but, as mentioned above, geochemical data are too rare to confirm this hypothesis.

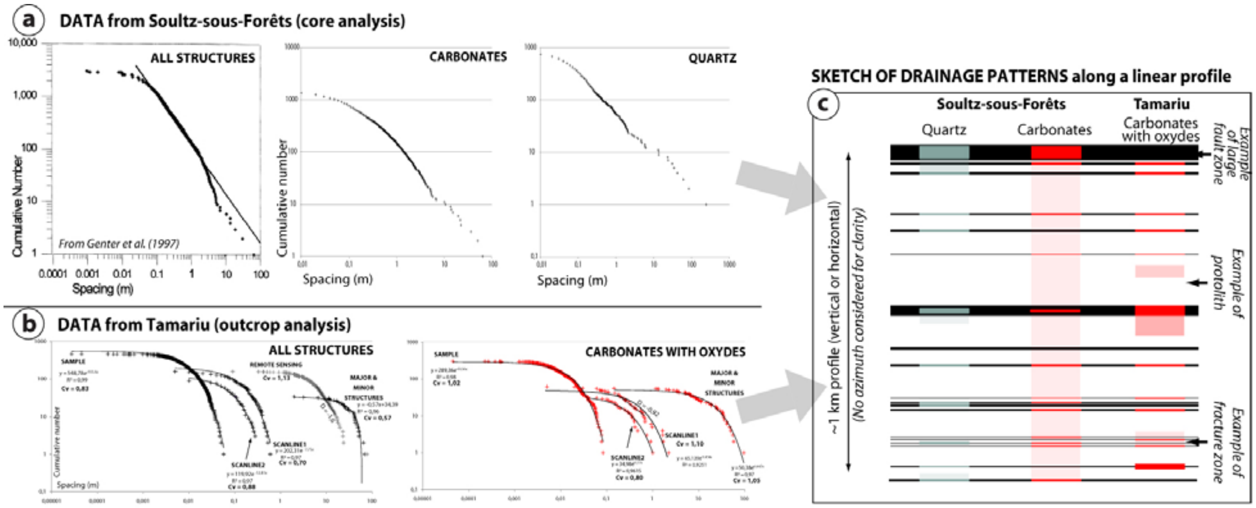


Figure 6: Distribution of spacing values by cumulative number analysis in Soultz EPS1 borehole (a) and in Tamariu outcrop (b). c) Sketch illustrating the percolated zones, within a given population of structures.

The Tamariu case study

As the data are collected on core, the approach exposed before is limited to the borehole trajectory. In addition, the crushing of cores from altered zones prevents their recovery at the surface. Thus, we carried out a similar survey on an outcropping analogue granite mass. As the outcrops in the shoulders of the Upper Rhine Graben are not large enough, we chose the Tamariu site in the Catalan Coastal Ranges where the variscan basement can be continuously followed over 1 km thanks to the active marine leaching (Fig. 7).

First of all, we mapped lineaments from DEM (in light gray, Fig. 7a) and satellite pictures analyses (in blue). A field approach was necessary to distinguish major and minor structures (in white and black, Fig. 7a).

Carbonate veins containing a high content of oxides have been observed. They form thick breccia (Fig. 7b) or dense network of fine veins (Fig. 7c). Oxygen isotopes and Rare Earth Elements indicate that they have formed in the 170-190°C temperature range in hydrothermal conditions. Thus, one can consider that they represent a circulation network in conditions similar to present-day EGS such as the Soultz-sous-Forêts example. Consequently, it was worth mapping this system in order to study the geometry of the fracture network percolated by the fluids.

We have mapped thick (thickness ≥ 5 cm) and thin (1 cm < thickness < 5 cm) veins (Fig. 7d). For convenience regarding thinner veins, we distinguished zones in which the cumulative thickness of little individual veins is greater than 1% of the rock mass (zones 1), or varying between 0.1 and 1 % (zones 2).

The first observation is that the distribution of the veins is heterogeneous at the scale of the outcrop (Fig. 7d). Some places present very dense concentration of carbonates, in some other the carbonates are lacking. These irregularities do not seem to be related to the position of major structures: for instance, in the vicinity of the fault bordering the blocks 2 and 3 the veins are quite rare, whereas they get denser in the vicinity of the structure of the same trend bordering the blocks 3 and 4. In other words, no correlation can be found between the carbonates content of the structures and the deformation/alteration accommodated/suffered by the structures. The second observation is that the orientation of the veins may vary from one block to another. Nevertheless, the total amount of data exhibits a coherent pattern, with a major set trending N060°E and to other sets trending N020°E and N100°E. This could be a signature of an emplacement during a single tectonic event where the mean horizontal stress would have been oriented N060°E.

This mapping has been continued at lower scales: a fractured corridor intensively affected by veins has been selected in the area indicated by dotted black line (Fig. 7d). At small scale, a similar mapping has been carried out on a sample indicated as B0935 in Fig. 7d.

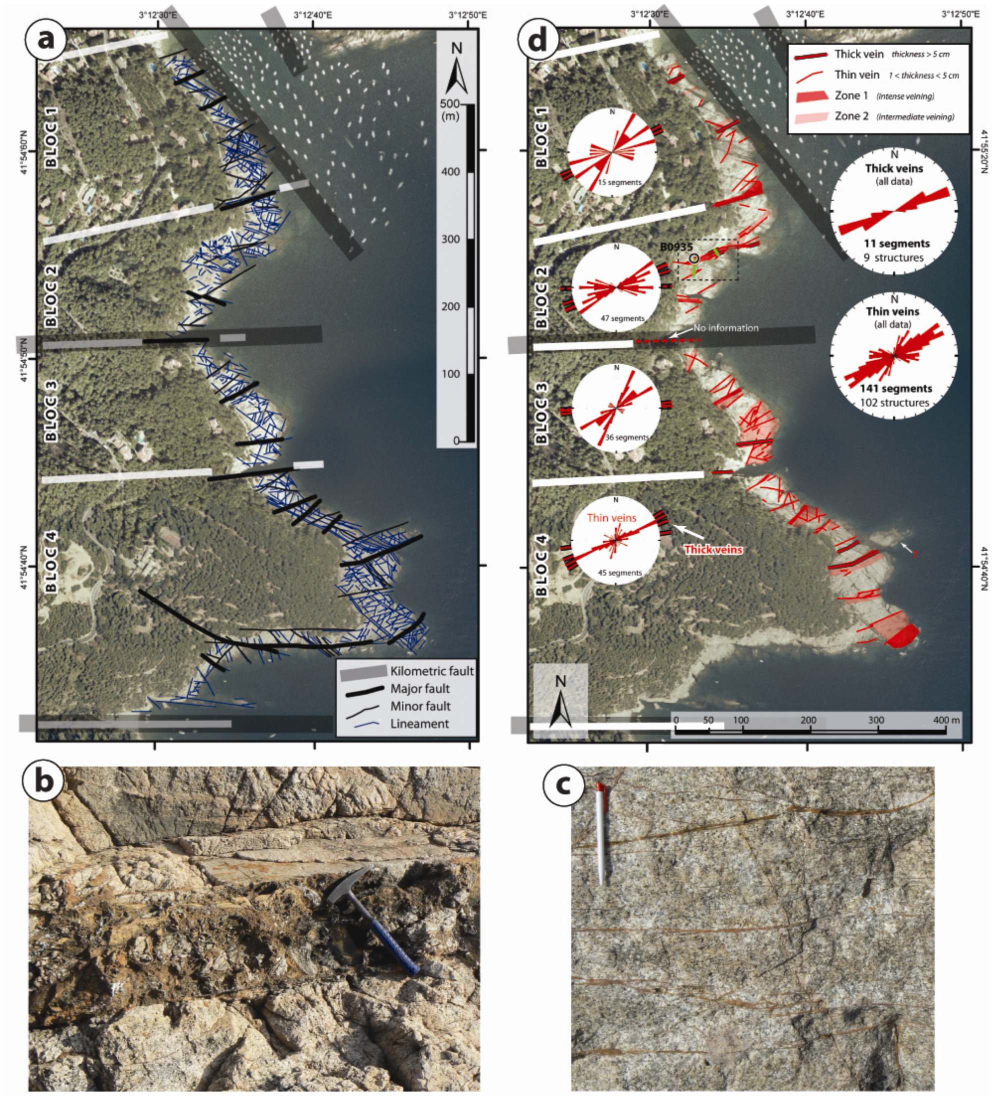


Figure 7: The Tamariu outcrop, located in the Catalan Coastal Ranges. a) Structural map from DEM, satellite pictures and field observations. b)&c) Carbonate veins rich in oxides forming for instance large breccia (b) or dense vein networks (c). d) Structural map of these carbonate veins.

Spacing distributions of all the structures or structures containing carbonates with oxides are reported in Fig. 6b. No power law distribution is observed. In general, the distributions are fitted by negative exponential laws. This is the signature of random distributions of structures (in black, Fig. 6) and veins (in red). The random distribution of veins in the structural network reflects the observation stated above (the location of veins do not depend on the alteration level of the structures).

Data were sorted depending on their trend: structures with azimuth values ranging between N040°E and N080°E produced similar distribution. This fact excludes the origin of random distribution by the melting of different populations of structures.

Synthesis of results

In Soultz-sous-Forêts, the quartz veins occur mainly in fault zones and altered zones. This distribution is drawn in Fig. 6c. The carbonate veins are distributed more regularly in the granite mass, both in fault zones and in protolithe (Fig. 6c). Nevertheless, a certain dependence of the location of the veins on the structural network is observed. The carbonate veins observed at Tamariu exhibit another distribution: the location seems random, independent from hierarchies in alteration degree or in deformational processes. This distribution can be represented in the sketch (Fig. 6c) with significant vein concentrations/absence locally in protolithe or in some major structures.

CONCLUSION

To resume, this paper presents some techniques and results about the characterisation of flow paths in fractured granites. Both present day and past circulation geometries have been investigated.

This paper shows that a sedimentary cover is very useful to document the most recent fault positions and their period of activity. However, it is also illustrated that such a cover can obstruct the access to the underlying granite where the geothermal resource is located. It is shown how the investigation of the cover can mislead the geologist about the structural network within the basement, for instance because of decollements. As a consequence, further investigations have to be carried out specifically in the basement or on analogues in order to characterise the structure network and its control on fluid flows.

In the Soultz-sous-Forêts geothermal site, seismic data (VSP) and core analysis have shown at different scales that the structural inheritance can be of major importance in present and past fluid flows, due to reactivation. These results are integrated into the reservoir model, becoming more and more realistic thanks to new data and ideas, and helping a clever management of the heat resource.

Three different types of distributions of percolated structures have been identified. Although geochemical data are too poor to reconstruct precisely the history of the circulation phases and their conditions (T, P, strain regime…), our simple approach from both an EGS site and a surface analogue shows that very different kinds of circulation networks can be activated in fractured granites.

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REFERENCES

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Al-Ali, Z. A., et al. (2009), Looking deep into the reservoir, Oilfield Review, 21(2), 38-47.

Aquilina, L., J.-R. De Dreuzy, O. Bour, and P. Davy (2004), Porosity and fluid velocities in the upper continental crust (2 to 4 km) inferred from injection tests at the Soultz-sous-Forêts geothermal site, Geochimica et Cosmochimica Acta, 68(11), 2405-2415.

Arthaud, F., and P. Matte (1975), Les décrochements tardi-hercyniens du sud-ouest de l'Europe. Géométrie et essai de reconstitution des conditions de la déformation, Tectonophysics, 25, 139-171.

Beauce, A., H. Fabriol, D. Le Masne, C. Cavoit, P. Mechler, and X. K. Chen (1991), Seismic studies on the HDR site of Soultz-sous-Forets (Alsace, France), Geothermal Science and Technology, 3, 239-266.

Bourgeois, O., M. Ford, M. Diraison, C. Le Carlier de Veslud, M. Gerbault, R. Pik, N. Ruby, and S. Bonnet (2007), Separation of rifting and lithospheric folding signatures in the NW-Alpine foreland., International Journal of Earth Sciences, 96, 1003-1031.

Cautru, J. P. (1989), Coupe géologique passant par le forage GPK1 calée sur la sismique réflexion, et documents annexes, edited, IMRG, EEIG "Heat Mining" Internal Report, Kutzenhausen, France.

Cocherie, A., C. Guerrot, C. M. Fanning, and A. Genter (2004), Datation U-Pb des deux faciès du granite de Soultz (Fossé rhénan, France), Comptes Rendus Geosciences, 336(9), 775-787.

Cosma, C., P. Heikkinen, J. Keskinen, and N. Enescu (2001), VSP in cristalline rocks-from downhole velocity profiling to 3-D fracture mapping, International Journal of Rocks Mechanics & Mining Sciences, 38, 843-850.

Dezayes, C. (1995), Caractérisation et interprétation d'un volume rocheux fracturé à partir de données de forages. Les forages géothermiques de Soultz-sous-Forêts et autres exemples d'échantillonnages unidirectionnels., Thèse de l'Université de Savoie, pp. 246.

Dèzes, P., S. M. Schmid, and P. A. Ziegler (2004), Evolution of the European Cenozoic Rift System: interaction of the Alpine and Pyrenean orogens with their foreland lithosphere, Tectonophysics, 389(1-2), 1-33.

Dylikowski, J. (1985), Etude en stratigraphie sismique de remplissage tertiaire de la région de Péchelbronn (Fossé Rhénan). Application au développement pétrolier en domaine de fossé d'effondrement, Université de Paris Orsay, Phd Thesis, Paris, France.

Édel, J. B., and K. Schulmann (2009), Geophysical constraints and model of the "Saxothuringian and Rhenohercynian subductions – magmatic arc system" in NE France and SW Germany, Bulletin de la Société Géologique de France, 180(6), 545-558.

Édel, J. B., K. Schulmann, and Y. Rotstein (2007), The Variscan tectonic inheritance of the Upper Rhine Graben: evidence of reactivations in the Lias, Late Eocene–Oligocene up to the recent, International Journal of Earth Sciences, 96(2), 305-325.

Emsley, S. J., P. Shiner, N. Enescu, A. Beccacini, and C. Cosma (2007), Using VSP surveys to bridge the scale gap between well and seismic data, Geological Society, London, Special Publications, 270(1), 83-91.

Evans, K. F., A. Genter, and J. Sausse (2005), Permeability creation and damage due to massive fluid injections into granite at 3.5 km at Soultz: 1. Borehole observations, Journal of Geophysical Research, 110(B04203), pp. 19.

Franke, W. (2006), The variscan orogen in Central Europe: construction and collapse, Geological Society, London, Memoirs, 32, 333-343.

Genter, A. (1993), Géométrie des zones fracturées et hydrothermalisées dans le granite de Soultz-sous-Forêts (forages GPK-1 et EPS-1), Note Technique Interne, BRGM N°RCS93T99, 15 july 1993.

Genter, A. (1999), Geological and well-logging data collected from 1987 to 1989 at the HDR site Soultz-sous-Forêts, Rapport BRGM/R-40795-FR, pp. 42.

Genter, A., K. Evans, N. Cuenot, D. Fritsch, and B. Sanjuan (2010), Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of enhanced geothermal systems (EGS), Comptes Rendus Geoscience, 342(7-8), 502-516.

Genter, A., C. Castaing, C. Dezayes, H. Tenzer, H. Traineau, and T. Villemin (1997), Comparative analysis of direct (core) and indirect (borehole imaging tools) collection of fracture data in the Hot Dry Rock Soultz reservoir (France), Journal of Geophysical Research, 102(B7), 15419-15431.

Gérard, A., and O. Kappelmeyer (1987), The Soultz-sous-Forets project, Geothermics, 16(4), 393-399.

Gillespie, P. A., C. B. Howard, J. J. Walsh, and J. Watterson (1993), Measurement and characterisation of spatial distributions of fractures, Tectonophysics, 226(1-4), 113-141.

Heidinger, P. (2010), Integral modeling and financial impact of the geothermal situation and power plant at Soultz-sous-Forêts, Comptes Rendus Geoscience, 342(7-8), 626-635.

Jones, R. H. (1993), Active seismic surveys at the Soultz site, Paper of EHDRA Scientific Conference May 1993, Soultz-sous-Forêts, France, pp. 4.

Le Bégat, S., F. H. Cornet, and V. Farra (1994), Etude de la percolation de fluides par sismique active sur le site de Soultz-sous-Forêts, Rapport rédigé pour l'Agence pour la Défense de l'Environnement et la Maîtrise de l'Energie, pp. 70.

Le Garzic, É. (2010), Distribution multi-échelle de la fracturation dans les réservoirs cristallins, influence de l'héritage structural. Exemples des marges obliques proximales du golfe d'Aden et de Catalogne., Ph.D. of the University of Strasbourg, pp. 268.

Luthi, S. M. (2005), Fractured reservoir analysis using modern geophysical well techniques: application to basement reservoirs in Vietnam, Geological Society, London, Special Publications, 240(1), 95-106.

Mari, J. L., F. Coppens, and J. Revol (2003), Well seismic surveying, Editions Technip, Paris, France, pp. 238.

Martí, D., J. Escuder Viruete, R. Carbonell, I. Flecha, and A. Pérez-Estaún (2006), Fault architecture and related distribution of physical properties in granitic massifs: geological and geophysical methodologies, Journal of Iberian Geology, 32(1), 95-112.

McCaffrey, K. J. W., J. M. Sleight, S. Pugliese, and R. E. Holdsworth (2003), Fracture formation and evolution in crystalline rocks: Insights from attribute analysis, Geological Society, London, Special Publications, 214(1), 109-124.

Petty, S., B. Livesay, M. Clyne, and R. Baria (2009), Bringing down the cost of EGS power, Geothermal Resources Council, Transactions, 33, 229-233.

Price, N. J., and J. W. Cosgrove (1990), Analysis of geological structures, Cambridge University Press, Cambridge, UK.

Rotstein, Y., and M. Schaming (2008), Tectonic implications of faulting styles along a rift margin: The boundary between the Rhine Graben and the Vosges Mountains, Tectonics, 27(2), pp. 19.

Sausse, J., M. Fourar, and A. Genter (2006), Permeability and alteration within the Soultz granite inferred from geophysical and flow log analysis, Geothermics, 35(5-6), 544-560.

Sausse, J., A. Genter, J.-L. Leroy, and M. Lespinasse (1998), Description et quantification des altérations filonniennes : paléoécoulements fluides dans le granite de Soultz-sous-Forêts (Bas-Rhin, France). Bulletin de la Société Géologique de France, 169(5), 655-664.

Sausse, J., C. Dezayes, L. Dorbath, A. Genter, and J. Place (2010), 3D model of fracture zones at Soultz-sous-Forêts based on geological data, image logs, induced microseismicity and vertical seismic profiles, Comptes Rendus Geoscience, 342(7-8), 531-545.

Schumacher, M. E. (2002), Upper Rhine Graben: Role of preexisting structures during rift evolution, Tectonics, 21(1), pp. 17.

Schutter, S. R. (2003), Hydrocarbon occurrence and exploration in and around igneous rocks, Geological Society, London, Special Publications, 214(1), 7-33.

Villemin, T., and F. Bergerat (1987), L'évolution structurale du fossé Rhénan au cours du Cénozoique : un bilan de la déformation et des effets thermiques de l'extension., Bulletin de la Société Géologique de France, 3, 245-256.

Ziegler, P. A. (1986), Geodynamic model for the Palaeozoic crustal consolidation of Western and Central Europe, Tectonophysics, 126(2-4), 303-328.

Ziegler, P. A. (1992), European Cenozoic rift system, Tectonophysics, 208(1-3), 91-111.

Ziegler, P. A., M. E. Schumacher, P. Dèzes, J.-D. Van Wees, and S. Cloetingh (2006), Post-Variscan evolution of the lithosphere in the area of the European Cenozoic Rift System, Geological Society, London, Memoirs, 32, 97-112.