Relative chronology of deep circulations within the fractured basement of the Upper Rhine Graben

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ABSTRACT

In the Upper Rhine Graben, the deep geothermal reservoirs constitute fractured dominated systems. However, the hydraulic behaviour of the fracture network is poorly known but its knowledge constitutes an important way to better target the exploration works.

In this paper, we propose a combined structural and mineralogical analysis of the fractures and their fillings based on samples collected on the EPS1 Soultz cores and outcrops on the both flanks of the Upper Rhine Graben. These mineralogical fillings have been sampled within fractures identified by measuring their orientation and defining their relative age. Petrological study (Optical microscope, Scanning Electron Microscope, cathodoluminescence) completed by chemical analyses (Electron Microprobe Analyses,) have been performed in order to determine the filling minerals and their relationships.

Several stages of fracturing following by several pulses of fluid have been occurred in the Rhine Graben. This study shows that the fracture sets are characterized by different polyphased mineralogical filling. In the Hercynian and Permian fracture sets two successive stages are highlighted: 1- shear/cataclasis phase with illite and quartz; 2- precipitation of dolomite. Those are the consequences of fluid circulation prior to the Oligocene graben opening. The N-S fractures linked to the Eocene-Oligocene graben formation, with reactivation of Hercynian structures, have no macroscopic mineralogical filling on outcrops because of surficial weathering alteration. However, under the microscope, tension fractures are filled with radial illite, which probably recorded fluid circulation associated to the early graben opening stage. The reactivation of Hercynian structures in relation with the Tertiary tectonic develops deep fluid/basement interaction. In the contrary, the N-S large structures are more recent circulation system and rather constitute recharge drain.

1. INTRODUCTION

In France, the geothermal heating production is mainly located in the great basins, such as the Paris Basin, but also the Aquitaine Basin and the Rhine Graben. The geothermal electricity is produced mainly in a volcanic context of Guadeloupe, and also in the experimental site of Soultz-sous-Forêts in Alsace. In the Upper Rhine Graben, geothermal projects are strongly under development, especially for the exploitation of fluid within the top of the basement. Numerous geothermal projects or exploration works are engaged for the exploitation of the deep geothermal energy for electricity or heating production, or cogeneration (electricity+heating).

In the frameworks of the geothermal exploration, we want to better understand the hydraulic behaviour of the fracture network, such as connexion, main fluid flow direction, role of the fault zones versus minor fractures, deformation types (cataclasis, fault, crack…).

For that, we propose to determine the nature of the palæo-circulations by studying fracture fillings, their textures and establish mineral sequence of fillings in relation to the tectonic phases and the geological history of the basement. Finally, the goal is to determine the relative chronology of circulation in the fractures in relation to the major tectonic events in the Rhine Graben area and the nature and origin of the palæo-fluids. The next step will be the comparison of the chemistry of palæo-fluids with those of present-day fluids which flow in the deeper part of the Upper Rhine Graben.

2. GEOLOGICAL CONTEXT

The Upper Rhine Graben is a Cenozoic graben belonging to the west European rift system (Ziegler, 1992), which is very well-known because of numerous studies for petroleum and mining exploration (boreholes, geophysical surveys…). The though is filling by Tertiary and Quaternary sediments with a rather discrete volcanic activity. This Tertiary cover overlays the Jurassic and Triassic sediments and the Paleozoic crystalline basement.

The crystalline basement has structured during the Hercynian orogeny linked to the NE-SW sutures occurred in the main tectonic phases at the Carboniferous (Sudete phase) and Permian (Saalian phase) (Zieger, 1986; Matte, 1986; Oncken *et al.*, 1999). In the Vosges (Schneider, 1984) and in the western border of graben (Villemin, 1986), these tectonic phases induce brittle tectonic with main fracture sets oriented N45°E, N135°E and N-S for the Carboniferous phase and N60°E to N90°E and N120°E for the Permian phase.

After a large period of sedimentation during Trias and Jurassic with clastic and carbonate deposits, the area has been uplifted from late Jurassic to early Eocene. The taphrogenesis started at Eocene by a N-S compression. The main phase of opening of the Rhine Graben occurred during Oligocene with an E-W extension. A second tectonic stage occurred during Miocene with a succession of two compressions, NE-SW and NW-SE respectively (Villemin and Bergerat, 1987).

Several local thermal anomalies are present along the western border main fault of the graben located near Obernai, Soultz, Landau (Schellschimdt *et al.*, 2002), which result from the circulation of deep fluids. All these anomalies are located where the direction of the border fault rotates from N20°E to N45°E (Figure 1).

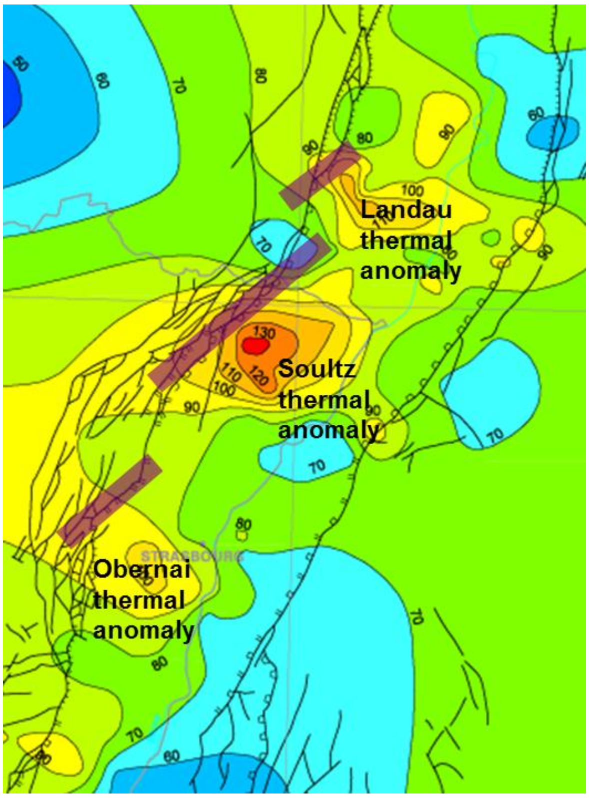

Figure 1: Interpolation of the temperatures at 1500m based on the GGA-Hannover data. The thermal anomalies are located near NE-SW direction of the western border fault.

Numerous saline, hot springs and spas (Niederbronn, Morsbronn, Baden-Baden) are present in surface and the experimental EGS project of Soultz exploits the deep geothermal resource of the graben (Genter *et al.*, 2012). These provided evidence of large scale fluid circulations at the sedimentary cover / granitic basement interface and down in granite (Pauwels *et al.*, 1993; Aquilina *et al.*, 1997, Sanjuan *et al.*, 2010). The origin of these fluids is common and should be from deep sedimentary reservoir such as lower Triassic at about 230°C (Pauwels *et al.*, 1993). Other authors show a fluid mixing, which suggests a part of meteoritic water from the Vosges massif (Cathelineau and Boiron, 2010).

On the basis of fluid inclusion studies in granite crosscut by the Soultz EPS1 drillhole, the earliest stage of pervasive alteration is characterized by hot moderately saline fluids (180–340°C; 2–7 wt% eq. NaCl) of late Hercynian age (Dubois *et al.*, 1996). Quartz-barite and quartz-ankerite veins containing a generation of lower temperature brines (130–160°C) with a large salinity range were attributed to younger, post Oligocene up to present day fluid-flow events (Dubois *et al.*, 1996, 2000).

3. METHODOLOGY

To discriminate the Hercynian and the graben opening brittle tectonics, we have revisited the fractures on the EPS1 well located on the Soultz site within the Rhine Graben and compared with fracture analysis on surface outcrops (Figure 2).

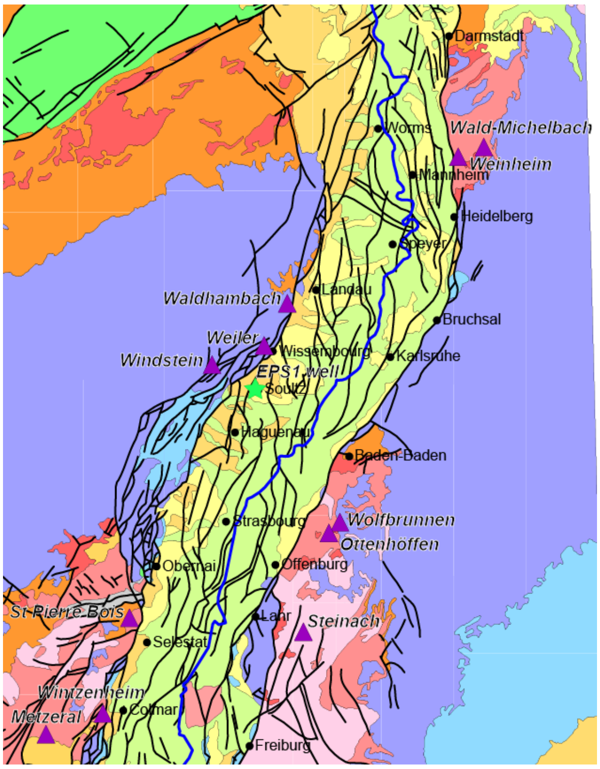

Figure 2: Location of the EPS1 well and the sampling sites in the granite basement near the main border faults.

The EPS1 borehole constitute the geological reference well of the EGS project. It was fully cored from about 1000m to 2220m, including 800m in the granite basement (Genter & Traineau; 1992). The basement reached by this well at 1417m depth, is constituted by a porphyritic monzogranite affected by both Hercynian and Tertiary tectonic events. The basement on the graben shoulders have the same Hercynian history but should not have the same Tertiary history after the uplift consecutive to the Oligocene extension. Moreover, this outcropping basement underwent a recent weathering, whereas the Soultz granite has been preserved. The mineralogical analysis of the granite cores from the EPS1 well allows having a base reference of the history record.

3.1 Collect of samples and structural analysis

The sampling aims at collecting structural measurements of fractures and faults linked to nature of their mineralogical filling (Figure 3).

Figure 3: Fracture with quartz filling and alteration halo in the granite.

Several outcrops have been visited in the granite basement along the main border faults at the both side of the graben (Figure 2). Generally, the sites are quarries, abandoned or with activities. On these outcrops, we have measured planes of fracture and fault, described the associated filling and the facture network relationship. Samples have been collected to detail mineralogy and micro-textures.

Six samples have been also collected among the granite cores of the EPS1 well on the EGS site of Soultz-sous-Forêts (Figure 2). They have been chosen among the most fractured intervals in the granite: 1) at the top of the granite and specifically in the 20 meters below the cover/granite interface at 1417 m, 2) at about 1650m and 3) close to the fractured zone at about 2150m (Figure 5).

3.2 Mineralogical determination methods

Optical microscope

Optical observations were performed using an Olympus BH2 microscope under transmitted and reflected lights. The size of mineral grains and particles were measured under the microscope using the Archimed software calibrated with a micrometer. The range of size given for each diagenetic phases are approximate and only given for information.

Scanning electron microscope

Observations and analyses with scanning electron microscope (SEM) were performed on polished thin sections of samples on a coupled with an energy dispersive spectrometer (Kevex Quantum) tuned at 25 kV. Prior to analysis, a 10–20 nm thick carbon layer was sputter-coated on thin polished sections (Edwards Auto 306).

Cathodoluminescence

Cathodoluminescence is a powerful tool to discriminate carbonates precipitated from different fluids because it is sensitive to trace element contents and to their crystalline framework. Mn^{2+} ion and trivalent REE ions appear to be the most important activator ions of extrinsic CL, whereas Fe^{2+} is the main quencher (Marshall, 1988; Richter *et al.*, 2003). The system used was a cold cathode Cathodyne from OPEA Society (Laboratoire Optique Electronique Appliquée). The electron beam has adjustable energies up to 26 keV and currents up to 250 µA. The cathodyne is mounted on a Olympus microscope allowing magnification up to 200. The system is equipped with a JVC KYF75U tri-CCD digital camera. The three 12 mm-sized sensors have a resolution of 1360 x 1024 pixels.

Electron microprobe

Spot analyses of carbonates were performed on polished thin section of samples covered with a carbon coating, using a CAMEBAX SX50 electron microprobe with an acceleration voltage of 15 kV, a current beam of 12 nA and a 1–2 lm beam width. Peak and background counting times were 10 s for major elements. Standards used included both well characterized natural minerals and synthetic oxides. Matrix corrections were made with a ZAF computing program.

4. RESULTS

4.1 Fracture orientations

The global orientation of the fracture measured on the field in the granite basement on the shoulders of the Rhine Graben shows different sets (Figure 4). In the southern part of the area, the main fracture set is oriented NW-SE associated to other sets N20°E and E-W (Figure 4). North, at Windstein and Waldhambach, we can observe the same main directions (Figure 4). In the both sites, Saint-Pierre-Bois and Wolfbrunnen, the main fracture set is oriented E-W (Figure 4). For the site within the Odenwald, in the north-east part, the main fracture set direction is N-S, associated with E-W direction set (Figure 4). Other fracture sets are also present in the different measured sites. Then, we can distinguish as main fracture sets: N0°E-N40°E, N100°E-N140°E, N60°E-N80°E and N150°E-N170°E.

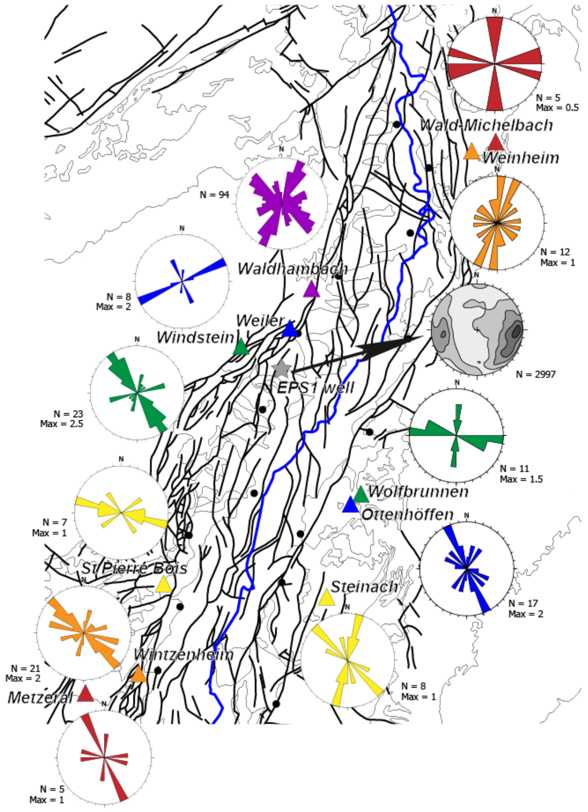

Figure 4: Direction of fractures measured on the granite outcrops and in the granite cores of EPS1 well. Rose diagram of strike direction with 10° classes. Contour-density diagrams in Schmidt's projection, lower hemisphere: 10%, 30%, 50%, 70%, and 90% of the maximum frequency.

On the cores of the Soultz well EPS1, numerous fractures have been observed (almost 3000 on 800m of borehole cores) and all orientations are represented (Figure 4) probably because all scales and types of fractures have been taking into account. However, some fracture sets can be highlighted. The main fracture set is oriented N-S to N20°E, with an associated set oriented E-W (Figure 4). Because of the long geological history of the granite, most of fractures are reactivated at different tectonic phases according to the relation between the fracture orientation and the direction of the stress field (Dezayes *et al.*, 1995).

The six core samples from the three main fractured intervals of the EPS1 granite were selected for the size of the fractures, the mineralogy, their specific orientations and their representativeness of the fracture interval (Figure 5).

The upper sample is located at 1418.43m depth, on the top of the granite, within the palæo-weathering alteration zone. This zone is characterized by a high density of subhorizontal fractures (about 15fr/m) with a N-S average direction. The two samples below at 1418.43m and 1434.31m depth are located in the upper fractured zone. Two individual fractures are sampling which are oriented N42°E-83° and N251°E-74° respectively. The sample at 1648.15m depth is located in a fracture oriented N310°E-28° included in a large cluster of fracture. The two lower samples are located in the 2100m fracture zone. They are at 2158.68m and 2161.66m depth respectively. The first one is oriented N-S, exactly at N270°E-81°, whereas the second one is NW-SE, N57°E-86°.

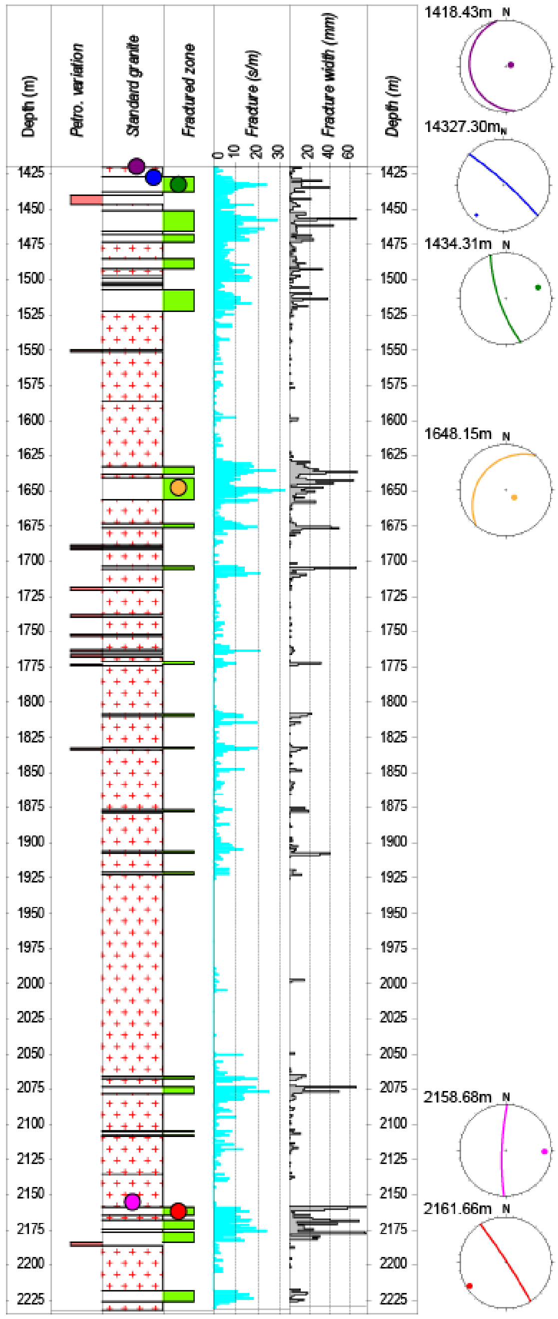

Figure 5: Orientation of fractures and location of the associated samples in the EPS1 well (log from Genter & Traineau, 1996).

4.2 Mineralogy of fracture filling

The major fracture fillings and alteration identified in granites from the Rhine Graben area consist of quartz ± illite with minor carbonates and sulfates. Carbonates are minerals of interest for two reasons. Firstly, from a geothermal point of view, they contribute to the clogging of fractures (Ledésert *et al*, 2009.). Secondly, from a scientific point of view, they are informative on the variations of fluid chemistry through geological times by combining their chemistry with mineral textural relationships. Cathodo-luminescence was useful in this study to distinguish yellowish orange calcite from dark red orange to light red orange dolomite, ankerite being dark due to inhibition of extrinsic luminescence by iron.

<u>EPS1 granite</u>

EPS1 core samples are firstly described and fractures fillings will be considered as reference types.

In the first (1418.43, 1427.30 and 1434.31 m) and second (1648.15 m) fracture intervals, the EPS1 biotite-amphibole porphyritic monzogranite is affected by a dense vein network and a high degree of alteration resulting from different generations of fracturation and fluid/rock interactions. The alteration of granite matrix consists of a large sericitization of plagioclase, illite + titanium oxides in replacement of early ferro-magnesian minerals (biotite, amphibole, muscovite), and quartz + carbonate + titanium oxides in replacement of titanite. Micron-sized grains of monazite were often identified by SEM in illite masses at the wall of the fractures.

The EPS1-1418.43 m sample was chosen for its numerous sub-horizontal fractures (N-S direction) which are characteristic of the top of the granite, attributed to a surface-stress relaxation effect during unroofing of the batholith in Permian times (Genter and Traineau, 1996). The infilling of the fractures consists of almost homogeneous dolomite. When numerous dolomite veins crosscut ancient biotite, biotite is entirely replaced by illite + dolomite + hematite. When micron-sized fissures penetrate into biotite sheet, biotite is replaced by yellowish illite with fibrous siderite intercalated in the sheets.

The EPS1-1427.30 m sample contains a NW-SE oriented and ~cm-thick reddish fracture corridor whose infilling is clearly polyphased (Figure 6):

1) shear/cataclasis with sericite mass/granite clasts cemented by illite and microquartz ; some micronic monazite grains are associated to this early stage;

2) euhedral quartz,

3) rhombohedral phantoms of Fe-bearing carbonates,

4) grey and quite pure dolomite alternating with ankerite, dolomite being dominant. Electron microprobe analyses of ankerite provide evidence of important Fe-Mg-Mn chemical zoning. Minor barite (Brt) occurs in residual porosity in dolomite.

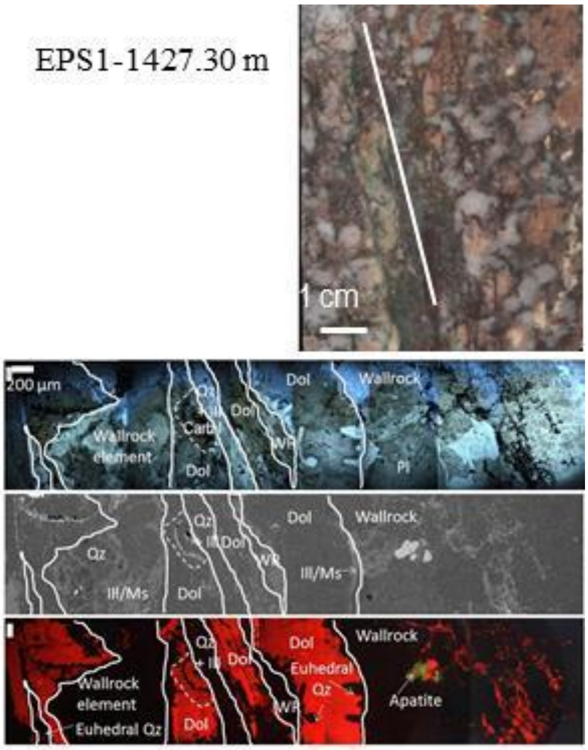

Figure 6: Photograph of the EPS1-1427.30m core sample showing the NW-SE fracture, and microphotograph of detailed texture and mineralogy of the polyphased fracture filling (natural light, BSE, CL).

The EPS1-1434.31 m sample contains two sub-parallel NNW-SSE <5 mm reddish fracture corridors, the largest one being crosscut by a fine white illite fissural plan. The mineral sequence of infilling is almost similar to those of EPS1-1427.30 m. However the microtextures are slightly different, by the fact that it is possible to observe micro-fissures with only one filling (sericite + microquartz or dolomite or ankerite). Moreover residual porosity is filled by ankerite and limpid quartz. Identification of phantoms of iron-bearing carbonates is rare, but is supported by the presence numerous iron-oxides associated with dolomite. Although illite fissures macroscopically seem to crosscut the reddish carbonate fracture, microscopically dolomite infills residual porosity and crosscut a illite+quartz cataclasic corridor.

The EPS1-1648.15m sample is crosscut by a network of micro-fissures in relation with a NE-SW ~5 mm thick fracture. The fracture corresponds to a network of sub-parallel illite ± quartz fissures. Iron-bearing dolomite (dark in cathodoluminescence) occurs as a discontinuous filling partially re-using this network before to penetrate in the granite matrix and form a 200-300µm-thick.

In the third fracture interval, the EPS1 granite shows reddish silicified zones alternated with pink less alternated zones. The density of fractures remains important. Mineralogy of the highly altered granite matrix (EPS1-2158.68 m) is almost similar to those observed in the both first and second fracture intervals. In a less altered sample (EPS1-2161.66 m), remnant chlorite and phantoms of titanite occur in place of primary biotite; this assemblage represents the early metamorphic/hydrothermal one identified in EPS1 granite.

The EPS1-2158.68m is crosscut by a network of calcite fissures. Siderite was rarely observed as fibrous lenses in sheets of altered biotite.

The EPS1-2161.43 m sample is crosscut by a NW-NE fracture, and by a network of fissures filled dominantly by ankerite with minor quartz. As it has been observed in the EPS1-1418.43 m sample, siderite occurs as fibrous lenses intercalated in sheets of altered biotite. Calcite occurs in altered plagioclase, but also in some fine veinlets crosscutting granite and also in sheets of altered biotite.

<u>Granites outcropping on the flanks of the Rhine graben</u>

Most of the outcropping granites are highly fractured; however macroscopic fillings of fractures are not abundant. And among filled fractures, quartz is the dominant mineral of filling which is identified on the field. This relative macroscopic homogeneity on the outcrops becomes more complex under the microscope in thin section (Table 1).

Table 1: Description of the microtextures associated to fractures observed in granites

Granites	Micro-textures observed under the microscope
Heidelberg (borehole He01)	1) Microshear/cataclasis with sericite mass/granite clasts, 2) euhedral carbonates
Metzeral	N170 : radial illite
Ottenhoffen	NW-SE, E-W: 1) cataclasis, 2) microquartz filling N-S: 1) cataclasis, 2) quartz/silica coating
Saint-Pierre-Bois	E-W: cataclasis
Waldhambach	NW-SE: 1) shear/cataclasis with sericite mass/granite clasts, 2) quartz filling, 3) Fe-bearing carbonates, 4) dolomite/ankerite, 5) barite
Windstein	NW-SE: 1) quartz vein, 2) cataclasis N-S: ill + µQtz
Wintzentheim	NE-SW: 1) Qtz infilling, 2) cataclasis
Wolfbrunnen	E-W: 1) cataclasis, 2) quartz filling N-S: 1) cataclasis

Samples from Waldhambach quarry (fresh outcrop), and Heidelberg borehole (HE01-140-147 m) are firstly described because they are different from other granites by the identification of carbonate filling in fractures. The both granites are biotite-amphibole monzogranite. Alteration of the fracture-free granite matrix is almost weak, marked by partial sericitisation of the plagioclase, partial to whole replacement of ferro-magnesian minerals by chlorite + illite ± epidote assemblage. Fractured granite samples are crosscut by NE-SW/NW-SE thin polyphased fractures. At Heidelberg, observed fractures are thin. The alteration of granite matrix remains unchanged. Fractures have an early stage characterized by altered granite clasts within sheared sericite mass, and late filling of euhedral carbonates. At Walhambach, details of a ~cm-thick fracture corridor (Figure 7) provide evidence of a polyphased filling very similar to those described in the EPS1-1427.30 m sample defined by:

1) shear/cataclasis with sericite mass/granite clasts cemented by illite and microquartz,

2) euhedral quartz growing of granite clasts of the fracture corridor,

3) successive infillings of dolomite, ankerite, Mn-ankerite, and finally barite.

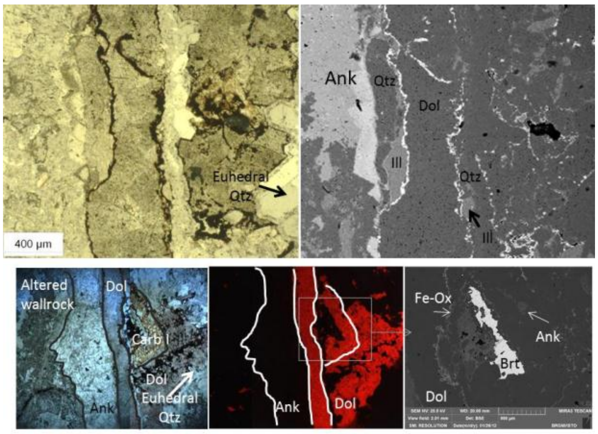

Figure 7: Microphotographs of detailed texture and mineralogy of the NW-SE polyphased fracture filling (natural light and corresponding BSE image, CL) crosscutting the Waldhambach sample.

The alteration of the fracture wallrocks is marked by intense sericitisation of plagioclase, partial recrystallization of muscovite flakes into illite, whole replacement of ferro-magnesian minerals by illite, titanium oxides, iron-oxides (hematite).

Granite samples from the other outcrops are dominantly biotite granite. Alteration of granite matrix whatever the fracture orientation is marked by sericitization of plagioclase and muscovite, and also partial to whole breakdown of biotite/chlorite into illite and hematite.

Two types of fractures can be distinguished: 1) fractures associated with cataclastic textures, and 2) fractures without shear displacement and cataclasis.

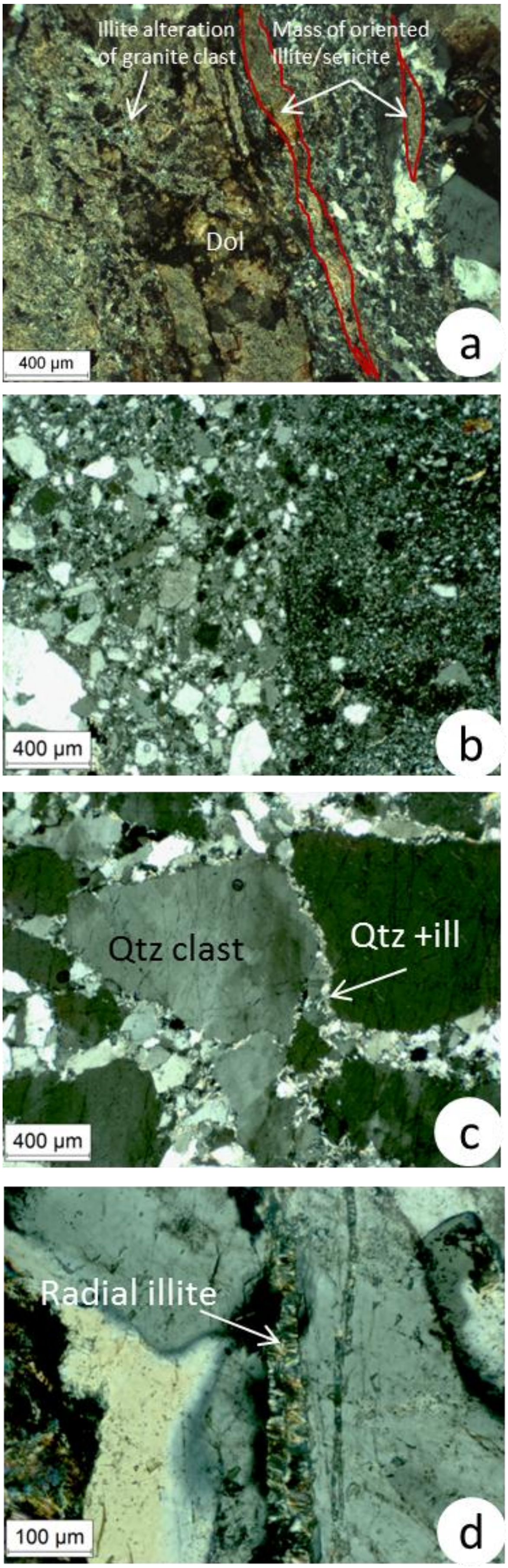

Figure 8: Microphotographs in polarized light of different types of fractures: (a) shear/cataclasis with sericite mass/granite clasts in a NW-SE fracture – Walhambach; (b) cataclastic texture in a E-W fracture – Saint-Pierre-Bois; (c) protocataclasis of a N50°E quartz vein crosscutting Wintzenheim granite; (d) N170°E fissure filled with radial illite, and crosscutting the Metzeral granite.

Cataclastic textures are observed in NE-SW/NW-SE, E-W and N-S structures (Figure 8a). They are all associated with microquartz and illite mixing. In NE-SW/NW-SE structures, filling of euhedral quartz (low temperature) later than cataclasis is observed at Ottenhoffen, whereas cataclasis affects borders of probable mesothermal quartz vein at Windstein and Wintzenheim.

Fractures without shear displacement filled with radial illite or radiale illite + quartz or carbonates + quartz are always observed in parts of granite which are preserved from direct weathering of meteoric waters. Most of them are <200 µm fractures not visible on the outcrop, and rather occur as a network of fissures than isolated fractures in thin section. For this reason, their orientation is often difficult to measure. Only well-preserved fissures filled with radial illite are oriented at ~N170 in the Metzeral granite (Figure 8b).

5. DISCUSSION

5.1 Relation fracture direction / filling

The determination of fracture infillings shows that some types of filling may be linked to the main identified fracture set directions (Figure 9).

<u>Fracture sets NE-SW, NW-SE and NNW-SSE</u>

These fracture sets are not dominant in EPS1 well within the Rhine graben. Petrological study of few samples from EPS1 containing fractures within these orientations provides evidence of polyphased fillings characterized by an early stage of shear/cataclasis with sericite mass/granite clasts cemented by illite and microquartz, and a late stage with dominant dolomite, and minor ankerite and calcite. The presence of dolomite/ankerite was already described (Dubois *et al.*, 1996, 2000; Genter and Traineau, 1996; Ledésert *et al.*, 2009) but their contents are probably underestimated in the bulk carbonate content.

These orientations are more represented in granites outcropping on the both sides of the Rhine graben. The same type of polyphased infilling including carbonates was only identified in place in the Walhambach granite; it could be the same in the granite crosscut by the Heidelberg borehole, but cores are not oriented. Elsewhere, these orientations are associated to cataclasis of mesothermal quartz vein (Windstein, Wintzenheim) or cataclased granite crosscut by few microquartz veinlets.

<u>Fracture set E-W</u>

Studied fractures belonging to this set are not frequent relative to the others. In the both granites affected by E-W fractures, this orientation is essentially associated to cataclasis (microquartz + illite) and no significant filling.

Fracture set N-S

Submeridian fracture set does not have macroscopic mineralogical fillings in outcrops. Fracture plans submitted to surficial alteration are generally very fresh and do not provide evidence of filling. In thin sections, two types of N-S fractures have been distinguished. Some major fracture corridors are associated to shearing, involving cataclasic textures and reworked quartz + illite fillings. Thin fractures preserved from direct surficial alteration do not have any shear displacement and are filled with radial illite. Alteration of granite matrix on the walls of the fracture is marked by a whole replacement of ferro-magnesian minerals and plagioclase by clay minerals with minor hematite.

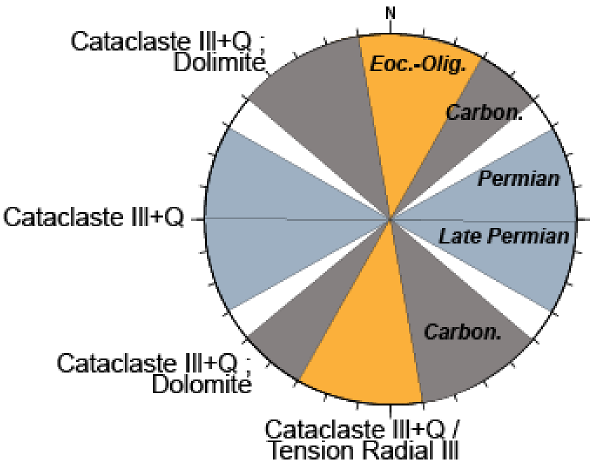

Figure 9: Synthesis of the main fracture directions in the granite with associated filling.

In spite of the long geological history of the Rhine Graben basement and the reactivation of most of fractures and faults, we can associate the main fracture sets to the tectonic phases (Figure 9). The submeridian set is associated to the main graben phases at Eocene N-S compression and Oligocene E-W extension, but this set is certainly reactivated from the Carboniferous sudete phase. The N30°E-N50°E and N140°E-N170°E sets are linked to the Carboniferous N-S compression. The N60°E-N80°E and N90°E-N120°E sets are linked to the last tectonic phases of the hercynian stages during the Permian, which correspond to extension before the collapse of the range and the peneplanain.

On the granite outcrops, the sebmeridian fracture set is not dominant, whereas it is the main set in the cores of EPS1 well. Then, the shoulders of the Rhine Graben are less affected by the brittle deformation linked to the Tertiary graben phases. Within the graben, the granite basement is largely affected by the Tertiary tectonic phases, which reactivate previous Hercynian fractures.

5.2 Age of fluid circulations

The relative chronology of the fluid circulations in the fracture network affecting granites of the Hercynian basement is complex, due to the superposition of the tectonic events but also to the precipitation/dissolution processes.

Concerning carbonate deposition in NE-SW, NW-SE and NNW-SSE fractures, a current petrological study of diagenesis in EPS1 Buntsandstein sandstones close to the cover/basement interface provides evidence of late diagenetic dolomite and ankerite. Similar compositions of carbonates in sandstones and fracture fillings in granite strongly suggest they resulted from similar large scale fluid circulations at the cover/granite interface confirming previous works (Dubois *et al.*, 1996, 2000), re-using Hercynian fracture framework. Up to now, dolomite and ankerite have been described simultaneously in polyphased fractures. These textures are interpreted as alternating deposition of ankerite/dolomite/ankerite in fracture corridors and suggest pulses of fluids. However, in this study, ankerite is also observed as filling of isolated fractures, suggesting disconnected fluids. Siderite was rarely observed as fibrous siderite intercalated in yellowish illite sheets when micron-sized fissures penetrate into biotite sheet, whereas dolomite, ankerite or calcite were observed elsewhere in fractures crosscutting granite. The presence of siderite restricted to altered biotite could be interpreted to local reaction between biotite and carbonate-bearing fluids, assuming a low fluid/rock ratio, as followed:

Biotite + fluid 1 = illite + siderite + fluid 2

Such ankerite fracture fillings at 1641 meters depth were attributed to post Oligocene up to present day fluid circulations (Dubois *et al.*, 1996, 2000). However, similar textures and carbonates were also observed in fracture corridors affecting the Waldhambach granite on the western flank of the Rhine Graben and in fractures affecting the granite of the Heidelberg borehole on the eastern flank, demonstrate that the fluid circulations associated to these fillings were already active at the cover/granite interface before the formation of the Rhine graben.

The formation temperatures of ankerite in the cover/granite context might be "estimated", taking account the burial curve of sediments at the cover/basement interface. In the Bundsandstein sandstones, ankerite and dolomite are late diagenetic phases formed later than quartz aureoles, and consequently at temperatures higher than 70-80°C. These temperatures are attained at the beginning of the graben formation, in relation with the mantle diapir.

Concerning N-S fractures in granites outcropping on the both sides of the Rhine Graben, cataclasis is the main process associated to their formation, but fillings are very rare. That strongly suggests that these structures could be considered as fractures favoring present-day recharge of fluid circulations in the Rhine

Graben. Same comments could be done for studied E-W structures.

However, some N-S fissures filled with radial illite were identified in the Metzeral granite. This morphology indicates authigenic illite. Illite is not formed under surface conditions. Consequently these fillings of radial illite could precipitate from moderate-temperature fluid at depth or from ascendant moderate-temperature fluids during the mantle diapirism at the early stage of the graben phase.

6. CONCLUSIONS

This study is an on-going work concerning the deep fluid circulation in the Rhine Graben based on a structural study linking to the analyses of their infillings. We have shown that the fracture sets are characterized by different polyphased mineralogical fillings. The analyses of the palæocirculation in the granite basement show that several stages of fracturing following by several pulses of fluid circulation have been occurred.

The Hercynian fractures, oriented NE-SW and NW-SE, show two successive stages of fillings:

1- A sheared/cataclased phase associated with illite and quartz;

2- Precipitation of dolomite in tension fractures.

The cataclasis stage associated with illite + quartz is present in the Hercynian and Permian fracture sets and also in the EPS1 well and in the Waldhambach outcrop. This shows that the fluid circulations, causing these fillings, are prior to the graben opening.

The carbonate, associated to this direction, precipitated later in relation with circulation between the basement and the sedimentary cover. The temperatures of carbonate formation are around 130°C (Dubois *et al.*, 1996). This could be the result of more recent circulations, probably during the early stage of the graben formation associated of the mantle diapirism.

A cataclasis stage is present in the N-S fractures. This fracture set is linked to the Eocene-Oligocene graben opening, with reactivation of Hercynian structures. On outcrops, this fracture set have no macroscopic mineralogical fillings, probably because fracture planes are submitted to surficial weathering alteration. However, under the microscope, tension fissures are filled with radial illite, which probably recorded fluid circulation associated to the early graben opening stage before the uplifting of the shoulders.

To conclude, the reactivation of old Hercynian structures in relation with the Tertiary tectonic history of the graben formation develops the fluid/basement interaction in deep temperature conditions. In the contrary, the N-S large structures favor recent circulation system and rather constitute a recharge drain.

This study has allowed determining the relative chronology of the fracture fillings in relation with tectonic events, but also having information on the chemistry of different fluids through geological times. This work constitutes the first step to understanding the palæo-circulations within the granite basement of the Rhine Graben. These textural and mineralogical data need to be completed by microthermometric, isotopic and geochronological investigations on well. Those give information of the fluid circulation within the fracture network to help exploration and development of future geothermal operation.

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