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Petrographic Analyzes of Fractured Granites used as An Analogue of the Soultz-sous-Forêts Geothermal Reservoir: Noble Hills, CA, USA

Johanne Klee[1*], Ghislain Trullenque[1], Béatrice Ledésert[2], Sébastien Potel[1], Ronan Hébert[2], Arezki Chabani[1], Albert Genter[3],

[1]Institut Polytechnique UniLaSalle, 19 rue Pierre Waguet, F-60000, Beauvais, France

[2]Université de Cergy-Pontoise, 1 rue Descartes, F-95000, Neuville sur Oise

[3]ES-Géothermie, 5 rue André Marie Ampère, F-67450, Mundolsheim

*johanne.klee@unilasalle.fr, others: ghislain.trullenque@unilasalle.fr, beatrice.ledesert@cyu.fr, sebastien.potel@unilasalle.fr, ronan.hebert@cyu.fr, arezki.chabani@unilasalle.fr, albert.genter@es.fr

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ABSTRACT

The work presented here is part of the European MEET project (Multidisciplinary and multi-context demonstration of EGS exploration and Exploitation Techniques and potentials), which aims to enhance demonstration of geothermal energy production throughout Europe. Petrographic analyzes of a geothermal reservoir are key issues for the understanding of fluid circulation in granitic rocks. Through field work, microscopical observations (optical microscope, SEM) and XRD analyzes, we aim at characterize a fractured and altered granitic body found in the Noble Hills (NH, Southern Death Valley, CA, USA) chosen as an analogue of the Soultz-sous-Forêts (SsF) geothermal reservoir (Upper Rhine Graben, Alsace, France). Our current state of knowledge reveals that the NH range is composed of a fractured and altered Mesozoic granitic body intruding Proterozoic sedimentary series. The composition of the granite and its alteration processes present similarities with the ones at SsF: oligoclase is transformed into kaolinite (tosudite at SsF)/ illite/calcite and biotite into chlorite/illite. The whole range suffers a substantial amount of shear deformation linked to the activity of the Southern Death Valley Fault Zone (SDVFZ) possibly much higher compare to SsF. A gradient of deformation can be followed through the range and along which samples were collected. Those ones reveal that the shear deformation can either reactivate mineralized fractures and create new drains for fluid circulation at low strain or promote the plugging of fractures due to the development of a high amount of clay minerals at high strain. Through analogue studies we here aim at 1) better understand the geometry of fluid circulation paths in the granitic fractured reservoirs and 2) gain insights in fluid rock interaction processes as these can drastically modify fractures properties through time.

1. INTRODUCTION

The H2020 MEET European project (Multidisciplinary and multi-context demonstration of EGS exploration and Exploitation Techniques and potentials) aims at improving of a deep geothermal reservoir by new exploitation and energy production techniques while continuing to explore and exploit the EGS (Enhanced Geothermal System) technology. In order to lower the cost and develop the use of geothermal energy in Europe the EGS technology must be developed in large variety of geological environments like intra-cratonic sedimentary basins and Variscan orogeny related terrains. Applying EGS techniques to Variscan domains are particularly challenging for a variety of reasons like 1) the complex geological history of the Variscan orogeny itself, 2) possible Alpine tectonic overprint and 3) the high anisotropy of the metamorphics rocks.

Reservoir understanding at depth is a prerequisite for a successful application of EGS technique. In the present study we aim at understanding fluid/rock interaction processes taking into consideration the amount of deformation affecting the reservoir. Our work is focused on the petrographical and petrophysical characterization of fractured granitic reservoirs and the SsF site is used as the demonstration site. Unfortunately access to the SsF reservoir is reduced to a limited amount of cores preventing a global geological understanding of the reservoir. Studies on analogues, i.e. exhumed fossil reservoir in which fluids have circulated are necessary to understand the evolution of fractured granitic reservoirs at large scale. In the following, we consider an analogue of a reservoir not as a true copy of the reference site but as an entity having similarities in term of structural and geological context and also in term of type of rocks. The main chosen analogue is the NH range located in the Death Valley in California (USA). It is proposed that progressive fracture sealing involving a combination of 1) fluid/rock interaction and precipitation of clay minerals and 2) deformation and associated dynamic recrystallization processes lead to variations in reservoir productivity at geological scale. Our model of evolution has important consequences in terms of targeting potential fractures systems at depth and adapting stimulation strategies.

2. THE MEET VARISCAN OROGENY APPROACH

The Variscan domain very often outcrops in Europe and is recognized for its good geothermal potential. Some gas wells crossing it have shown the occurence of a geothermal resource. In order to structure our approach, the Variscan domain has been divided in two main parts depending on the nature of the encountered rocks (Variscan metasediments and metavolcanics versus Variscan granitic basement) themselves divided in two groups depending on their tectonic history: Variscan domains affected by post Variscan extensional tectonics versus Variscan domains not affected by post Variscan extensional tectonics.

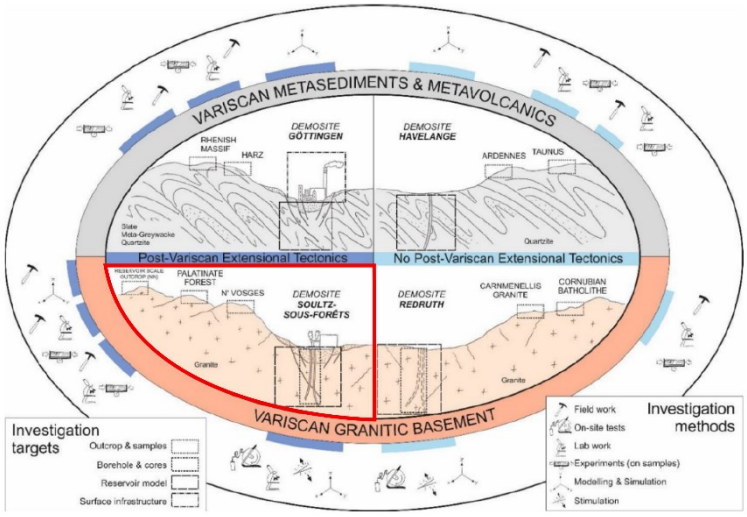


Figure 1: Schematic overview of the four representative European Variscan geotectonic settings including the demonstration sites, the analogue sites and the investigation methods according to (Trullenque et al., 2018). Our case study is framed in red.

The MEET project has a demonstration site each of these contexts (Figure 1) (Trullenque et al., 2018):

- Variscan metamorphic (metasedimentary and metavolcanic) successions overprinted by younger (mostly Cenozoic) extensional tectonics (rift system): demonstration site University of Göttingen (Germany)
- Variscan metamorphic (metasedimentary and metavolcanic) successions not overprinted by younger extensional tectonics: demonstration site Havelange (Belgium)
- Variscan crystalline basement overprinted by post-variscan extensional faults: demonstration site Soultz-sous-Forêts (France), which is our study (fig. 1)
- Variscan basement not overprinted by younger extensional faults: demonstration site Redruth (United Kingdom)

3. PRESENTATION OF THE DEMONSTRATION AND ANALOGUE SITES

3.1. Demonstration site: Soultz-sous-Forêts

3.1.1. Geological context

The SsF site is located within the Upper Rhine Graben (URG), which forms the central most conspicuous segment of the European Cenozoic Rift System (Ziegler, 1992), near its major western boundary fault (Figure 2a).

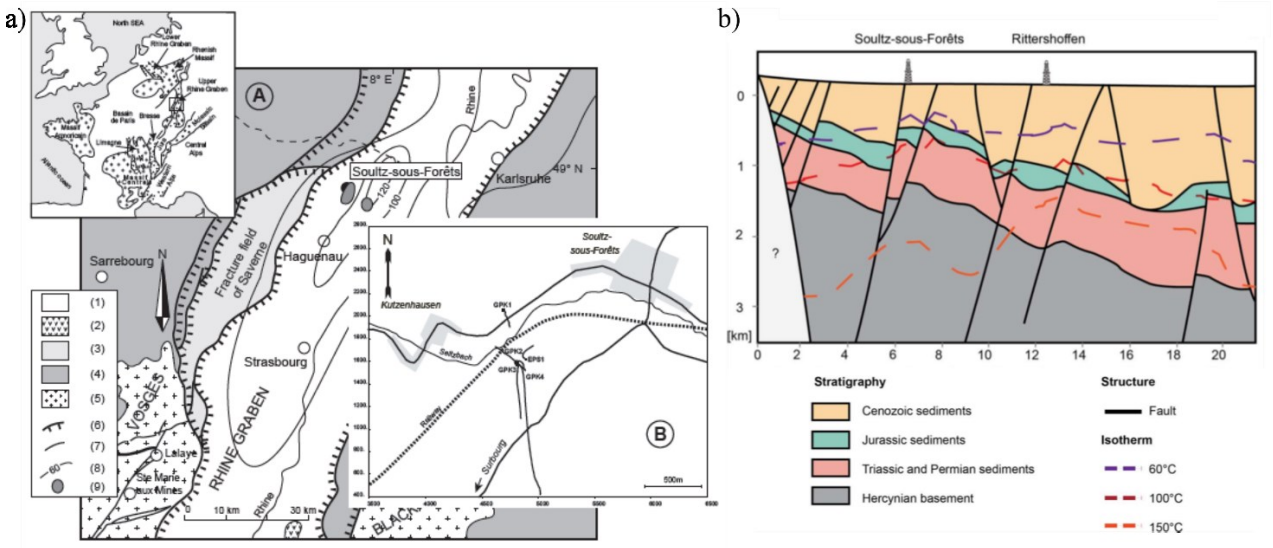


Figure 2: Figures presenting a) A: the location of the EGS Soultz-sous-Forêts site and geology of the URG and B: a local map of the Soultz-sous-Forêts site with the well trajectories. According to (Dezayes et al., 2004) and b) a simplified geological cross section and isotherms across Soultz-sous-Forêts and Rittershoffen geothermal plants (Vidal and Genter, 2018)

The URG originates in Paleogene times from the Alpine collision due to the build-up of far-field intraplate compressional stresses and is described as a typical example of syn-orogenic, intra-continental foreland rifting affected by Variscan crustal pre-

discontinuities (Ziegler, 1992;Dèzes et al., 2004). It has a NNE-trending which is limited by the Rhenish Massif to the north and the Jura Mountains to the south and has a length of some 300 km and a width of 30-40 km.

Three major terranes oriented NE to NNE characterize the Variscan crystalline basement of the URG. They are intruded by carboniferous granitoids (Visean (-340 Ma) and Permian (-270 Ma)) which are emplaced following the URG trending related to primary weakness zones such as collisional or shear zones. These Paleozoic crystalline basement rocks do not outcrop but are overlain by 1400 m of Mesozoic (Triassic and Jurassic) and Cenozoic sediments (Figure 2b). Rifting occurred during the Tertiary between the end of the Eocene and the beginning Miocene (Schumacher, 2002; Dezayes and Lerouge, 2019; Edel and Schulmann, 2009).

3.1.2. Soultz-sous-Forêts site

After an initial Hot Dry Rock (HDR) concept, SsF has evolved to an EGS technology which consists in hydraulic and/or chemical stimulations to increase the permeability and allow transport of the geothermal brine (Dezayes et al., 2010). In total five boreholes have been drilled but only three of them are used for reservoir development and heat exploitation. Those ones reach a depth of approximately 5000 m with temperatures up to 200°C.

All the wells exhibit at least one permeable fracture zone and the natural fracture network acts as a natural heat exchanger. The top of the granite is highly fractured with a fracture density average of 1 frc/m above 2000 m. Below, the fracture density decrease to 0.4 frc/m and in the deep part it increases to 0.6 frc/m between 4600 and 5100 m (Dezayes et al., 2004).

The SsF reservoir is characterized by the presence of highly fractured fault cores, which are surrounded by altered, porous and fractured damage zones. Through these fractures a highly saline fluid (100 g/L) circulates at a temperature between 130 and 150°C. Fault zones present a higher permeability for hydrothermally altered granitic basement than for hard fractured sandstones or poorly altered deep granitic basement (Vidal and Genter, 2018). Fracture fillings are heterogeneous, and polyphased, dominantly represented by quartz, barite, illite, carbonates, and iron oxides (Genter et al., 1995). Quartz veins are mainly localized into the fault core and correspond to the precipitation of silica-rich fluids derived from the dissolution of primary silicate minerals during vein alteration (Vidal and Genter, 2018). The hydrothermal alteration of the SsF granite is characterized by specific mineral assemblages and changes in bulk-rock chemical composition. It presents two major kinds of alteration: 1) a propylitic alteration linked to the cooling of the pluton, characterized by the partial transformation of biotite into chlorite and plagioclase into illite and newly formed epidote (Genter, 1989) and 2) a vein alteration due to fluid flowing within the fracture network which induces chemical leaching and clay enrichment processes (Genter, 1989; Ledesert et al., 1999; Pauwels et al., 1993). Alteration of primary minerals related to these water-rock interactions leads to the breakdown of: 1) plagioclase mainly into illite but also into tosudite in the SsF granite (Ledesert et al., 1999). Tosudite is considered as a geochemical analogue of kaolinite, but the occurrence of tosudite instead of the kaolinite can be explained by the amount of lithium present in the fluid (Pauwels et al., 1992) and 2) biotite into chlorite and illite. Primary K-feldspar and quartz are not affected by this alteration (Traineau et al., 1991). The URG granite has been affected during the Tertiary by several compressional and extensional tectonic phases developing a multiscale fracture network (Schumacher, 2002). This latter having suffered no more deformation let geothermal fluid flow through those open fractures. Glaas et al., (2019) argue that in the case of an open fracture, the fluid is mainly channeled in the core fault, precipitating drusy quartz and partially in the walls. However, when this fracture or vein is completely sealed by quartz or illite, only the open fractures present in the damage zone can act as fluid pathways (Figure 3).

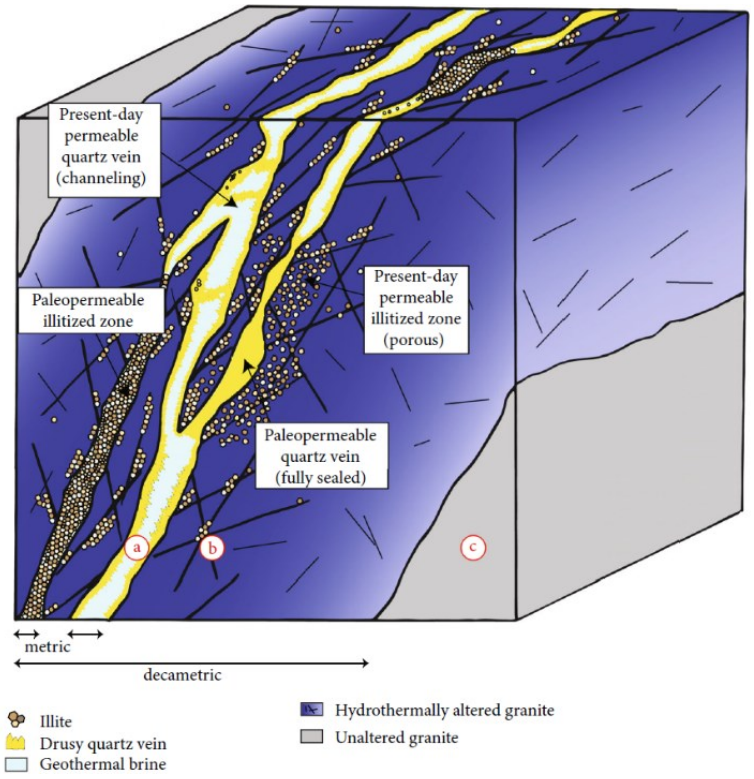


Figure 3: Block diagram from Glaas et al. (2019) representing the fluid circulation in a complex system of fault zones

In order to illustrate the above mentioned deformation and alteration features we present two core samples, SsF1 and SsF2, from borehole EPS1 taken at a depth of 2160 m (Measure Depth) and around 1400 meters respectively. Sample SsF1 (Figure 4) has been intensively investigated by Vidal and Genter, (2018) and originates from a major permeable fracture zone. It shows a prominent alteration gradient from the walls of the granitic veins away from it. Note that besides the vein opening and associated fluid circulation related alteration, the rock initial magmatic texture remains undisturbed. We notice in particular the lack of any cataclastic nor mylonitic deformation implying that no strain was applied along the vein walls after vein opening.

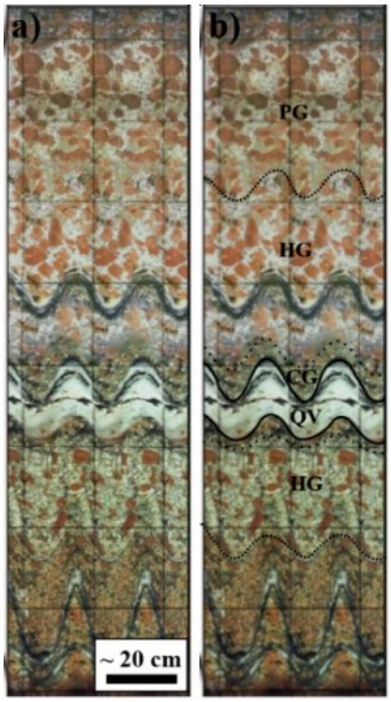


Figure 4: Sample SsF1. Scan of a core (laid flat and doubled) of major permeable fracture zones from EPS1 well at Soultz-sous-Forêts with a) the original scan and b) the different zonation characterizing the core. QV: Quartz vein; CG: Cataclased granite; HG: Hydrothermalized granite; PG: Porphyritic granite (modified after Vidal and Genter, 2018).

As described by (Glaas et al., 2019), only opened or filled fractures are investigated in the SsF reservoir. However, there is evidences of shearing as shown by the sample SsF2 (Figure 5). It exhibits intense shearing accommodated along a foliated and anastomosing cataclastic gouge with a clear gradient of alteration affecting the rest of the sample. Note the impressive stretching of the oxide precipitates and quartz ribbons related to post vein formation strain. This deformation zone is non-permeable for geothermal fluids as totally sealed by a large variety of dynamically recrystallized and neo-formed fine-grained minerals.

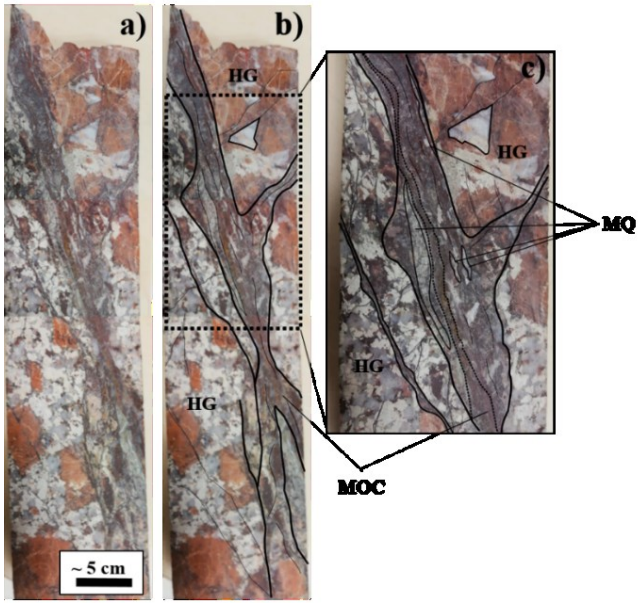


Figure 5: Sample SsF2. Picture of a longitudinal core cut section of a sheared and sealed fracture from EPS1 well at Soultz-sous-Forêts with a) the original picture, b) the different zonation characterizing the core and c) a zoom on the core. HG: Hydrothermalized granite; MQ: Mylonitic quartz as relicts; MOC: Mylonitic oxides and clays.

Deformation has an important impact on the evolution of the fault petrophysical properties (Wallace and Morris, 1986) and on the reservoir connectivity (Bailleux et al., 2011; Curewitz and Karson, 1997). That is why one part of this study focuses on varying deformation amounts accumulated on faults and their impact on fluid circulation and fluid/rock interaction processes.

3.2. Analogue site: Noble Hills

3.2.1. Death Valley geological context

The Death Valley region is located in the southwestern part of the Basin and Range province of southeastern California and southern Nevada (Figure 6) and is bounded on the west by the Panamint Range and the south by the Providence Mountains. The Death Valley region is one of the youngest regions of large-scale crustal extension within the Basin and Range province. This extension occurred from the Miocene to the Holocene. Normal and associated strike-slip faulting accompanied by the extensional basin formation began < 15 Ma and continuous today (Calzia and Rämö, 2000).

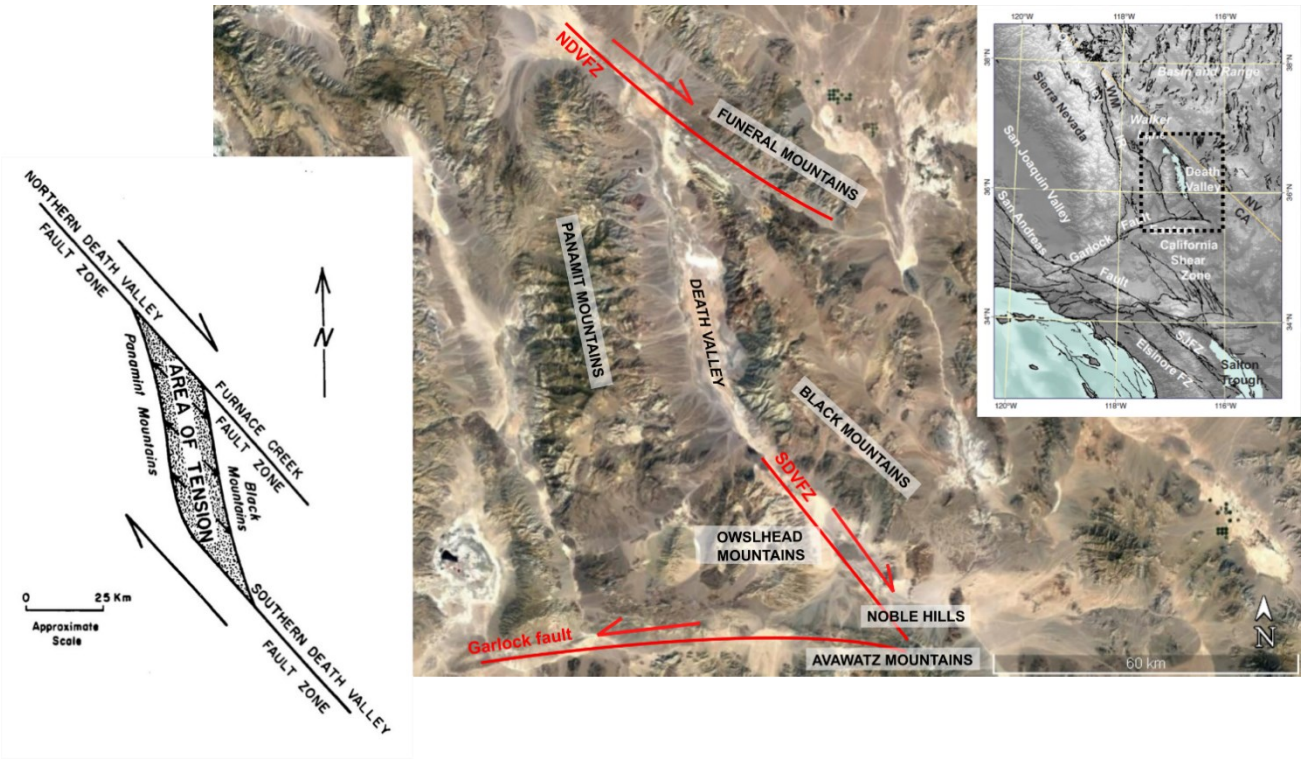


Figure 6: Location of Death Valley and tectonic domains modified after ((Burchfiel and Stewart, 1966; Norton, 2011) NDVFZ – Northern Death Valley Fault Zone; SDVFZ – Southern Death Valley Fault Zone

The Southern Death Valley Fault Zone (SDVFZ) is part of the northwest-trending, right-lateral, strike-slip system of faults located in southern Death Valley. Along with the Northern Death Valley-Furnace Creek Fault Zone (NDVFZ), the SDVFZ appears to be related to extension within the southern Basin and Range province (Stewart, 1983) and so makes up the southern component of the Death Valley fault system (DVFS) (Machette et al., 2001). Near its southern end, the fault zone intersects the east-trending, left-lateral Garlock fault which is linked to the San Andreas Fault (Calzia and Rämö, 2000). A right-lateral offset of ~35 km has been defined, based on matching offset alluvial fan ravel with its source area. It refined earlier estimates of 8 to 80 km of movement for the SDVFZ (Butler et al., 1988) and is consistent with the geometry of a pull-apart basin model for central Death Valley defined by Burchfiel and Stewart, 1966. Recently, (Pavlis and Trullenque, Submitted) have proposed a net amount of 40 to 41 km strike-slip along the SDVFZ based on correlation of a set of geological markers between the Owlshead and the southern termination of the Noble Hills.

In this region the pre-Cenozoic stratigraphy consists of Early Proterozoic cratonic rocks and Middle Proterozoic sedimentary paragneiss, schist, and quartzite intruded by ca.1700 Ma orthogneiss and 1400 Ma anorogenic granites (Wooden and Miller, 1990). The Middle Proterozoic Pahrump Group unconformably overlies the cratonic rocks and is overlain by 3000-5000 m of Late Proterozoic and Paleozoic miogeoclinal deposits. It consists of ~2100 m of conglomerate, sandstone, shale, and carbonate rocks divided into three formations: the Crystal Spring Formation, Beck Spring Dolomite, and Kingstone Peak Formation. The first one, Crystal Spring Formation, is intruded by 1068 Ma and 1087 Ma diabase sills. Most of the Proterozoic and Paleozoic rocks are intruded by Mesozoic and Tertiary plutons. All these rocks are overlain by later Tertiary sedimentary and volcanic rocks and Quaternary alluvial deposits. Note that numerous granitic plutons, dikes, and sills are synchronous with extension (Calzia and Rämö, 2000).

3.2.2. The Noble Hills range.

The Noble Hills (NH) are located in the southernmost part of the Death Valley region and trend parallel to the SDVFZ at its southern end (Figure 6). Troxel and Butler, (1979) characterized the SDVFZ as a zone of multiple, subparallel, overlapping right-lateral fault strands extending northwest the length of the NH from the foothills of the Avawatz. In the NH, the SDVFZ juxtaposes Tertiary and Quaternary strata against crystalline basement rocks also called “axial crystalline ridge” (Brady III, 1986). This one comprises

Precambrian Crystal Springs Formation of the Pahrump Group and is intruded by undifferentiated Mesozoic granitic rocks which crop out and locally by 1.1 Ga diabase sills (Troxel and Butler, 1979).

A combination of GIS assisted field work mapping and intensive sampling of the area were realized. Regarding mapping we revisited the work of Niles, 2016. It was conducted in the field by using satellite imagery and supported by our own observations. Structural data were collected on all the area to have a general overview of the kinematic of the NH. The mapping revealed a complex geometry with several repetitions of the Proterozoic sedimentary cover. A perfect continuity of those series as well as granite is observed southeastward together with an impressive stretching linked to the dextral shear activity of the SDVFZ, which shows an increasing deformation gradient toward the south east (Figure 7).

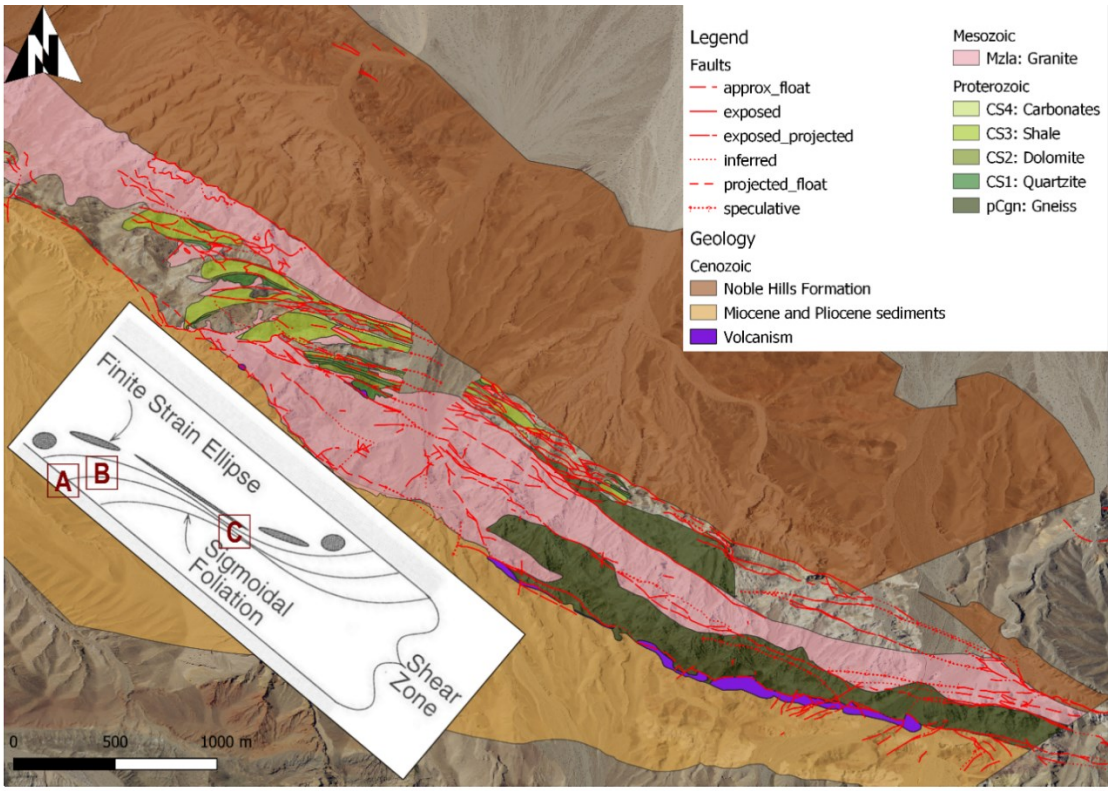


Figure 7: Geological map of the Noble Hills range realized from field investigations (ongoing work) and after Niles (2016) compared to a scheme of a shear zone (https://slideplayer.com/slide/3405849). A, B and C correspond to samples collected along the deformation gradient.

4. PETROGRAPHIC CHARACTERIZATION

4.1 Hydrothermal alteration of the granitic basement

The sampling was done 1) in a homogeneous way to cover the study area as much as possible and 2) following the gradient of deformation. Thin sections were investigated for each of the 37 samples collected in the field. An accurate optical microscopic study allowed to determine the mineralogical composition of each sample. The main primary minerals are feldspars (plagioclases and K-feldspars), quartz and biotite. More precisely, plagioclase, in our case oligoclase, are the most abundant. According to (Streckeisen, 1973) the composition corresponds to a granite/granodiorite. Moreover, it has been observed that the samples present signs of alteration due to a fluid circulation. This alteration affects plagioclase and sometimes biotite. Quartz and K-feldspar remain intact. Plagioclase alteration initiates at the center of the mineral (Figure 8a and b) and spreads to the edge. They are transformed into kaolinite (Figure 8c) and into illite (Figure 8d). Cathodoluminescence observations (Figure 8b) show that plagioclase can present a Na-rich rim (in blue) attributed to albite, and can contain calcite.

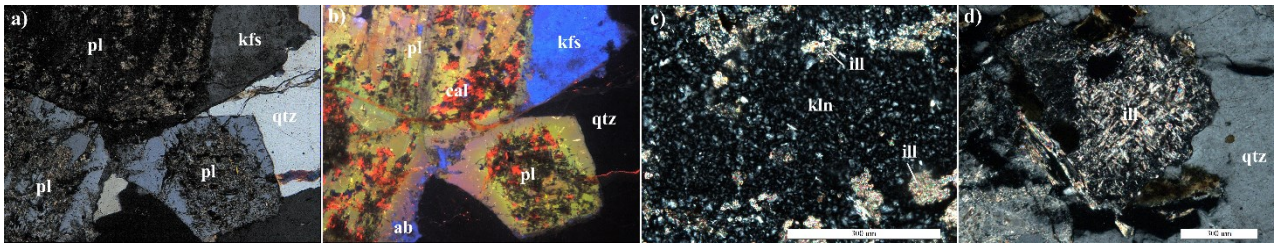


Figure 8: Images a) of altered plagioclases under optical microscope in polarized and analyzed light, b) of the same plagioclases than a) under cathodoluminescence presenting the calcite in red, in pink-green the plagioclases with a blueish albite rim and also in blue the K-feldspars, c) kaolinite and illite as plagioclase pseudomorphosis products under optical

microscope in cross polarized light and d) of an altered plagioclase with illite precipitation under optical microscope in cross polarized light

When observed with a scanning electron microscope coupled with an energy dispersive spectrometer (SEM-EDS), plagioclase shows corrosion pits and zones where kaolinite has crystallized, replacing plagioclase. A focus on kaolinite is given in Figure 9, showing hexagonal particles organized in fan shape. Illite (Figure 8d) and also calcite are precipitating. During the alteration of plagioclase Ca was released which contributed to the precipitation of carbonates, here nearly pure calcite. The samples generally have a high amount, up to 10% of carbonates (calcite and dolomite) occurring mainly as veinlets. However, it is unlikely that such a high amount of calcite is only related to the alteration of the plagioclases. Since Precambrian age dolomites crop out within the Noble Hills, i.e. in direct vicinity of the granite. It is conceivable that the fluid got enriched in Ca and Na while crossing the dolomite units to finally precipitate carbonates in the fracture network affecting the granitic basement.

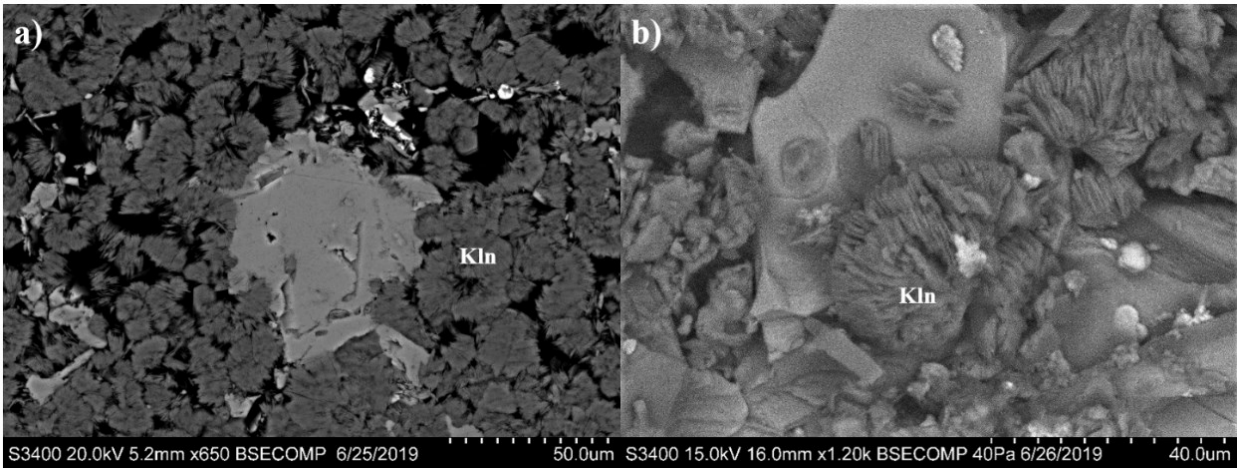


Figure 9: Images of kaolinite of the same sample under SEM of a) the thin section and b) a piece of the sample

Biotite alteration is less pronounced than that of plagioclase. Large patches of biotite are indeed still recognizable in thin sections (Figure 10). According to SEM-EDS analyzes, the product of biotite alteration contains only K, Al, Si and O (no Mg and Fe) and corresponds to illite. This type of transformation is also observed on biotite in the SsF granite (Bartier et al., 2008; Ledesert et al., 1999). The lack of Mg and Fe could be due to the extraction from biotite during alteration and seems to be confirmed by the occurrence of oxides surrounding altered biotite as visible in Figure 10. Further SEM investigations and Mass Balance Calculations are planned to confirm this hypothesis in other samples.

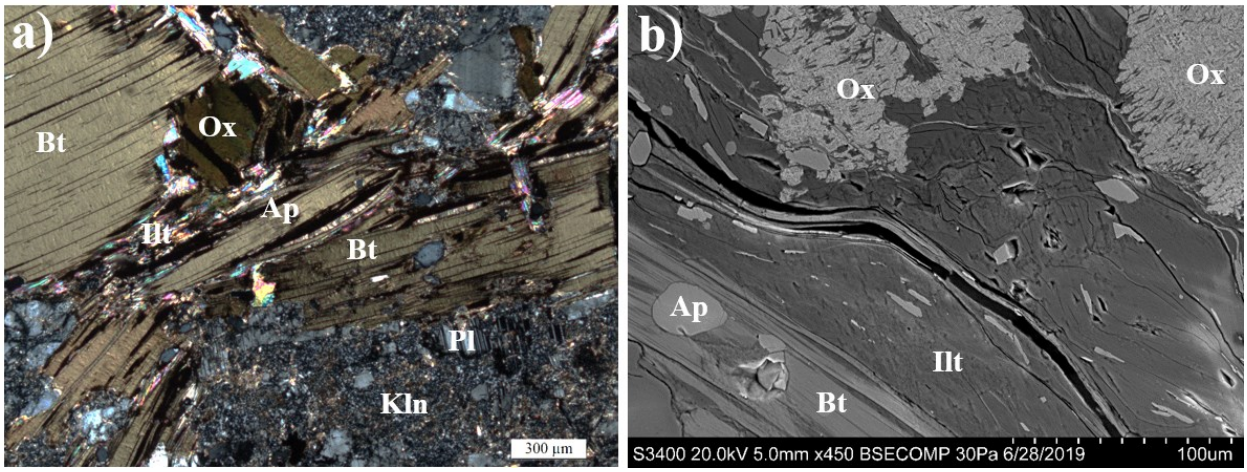


Figure 10: Images of slightly altered biotite, a) under polarized and analyzed light and b) under SEM

Samples present sign of dynamic recrystallization processes affecting quartz. Bulging recrystallization develop at the boundary between quartz crystals indicating a temperature around 300°C (Stipp et al., 2002). XRD analyzes were performed on these samples and, based on the illite crystallinity (Kübler, 1968), data show a low degree of metamorphism with temperature lower than 300°C. This apparent contradiction in term of temperature can be explained by the fact that the system has been potentially reset with time due to fluid circulation and deformation. K/Ar dating on illite is underway to replace the fault within the historical context and answer to this question.

4.2 Fault zones fluid circulation associated to the amount of deformation

As already announced, the Noble Hills granite present an intense gradient of deformation. Three zones (A, B and C on Figure 7) were chosen along this gradient in order to describe the response of granitic rock to strain. The aim is to see the influence of the deformation on the fluid circulation.

The zone A is characterized by a granite presenting incipient signs of deformation. Fractures are filled by secondary mineral precipitations as carbonates (Figure 11a), oxides, barite (Figure 11b). Those fractures had to act as the main fluid channels before their complete sealing. Due to this concentrated fluid flow in the fracture, the walls develop a decreasing alteration halo by moving away from the fracture.

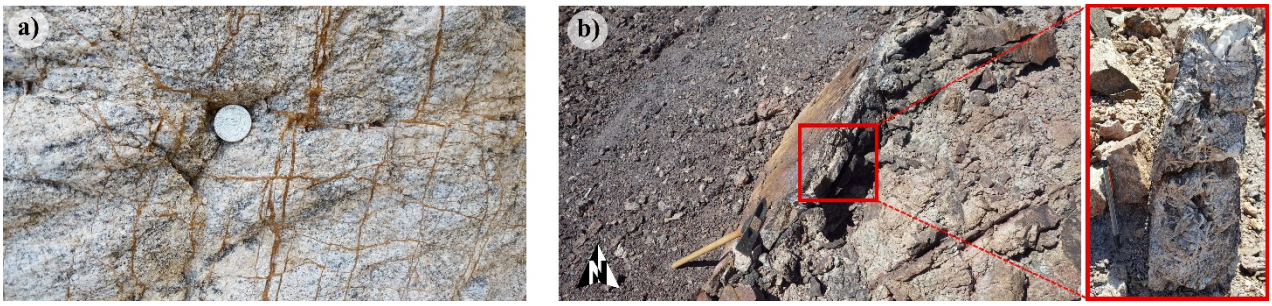


Figure 11: Pictures from zone A presenting a) an altered granite rich in carbonates veins and b) a fracture filled by automorphy barite

The zone B (Figure 7) manifests a low strain illustrated by the sample presented in Figure 12. This sample shows: 1) a pronounced alteration gradient from either side of the fracture and 2) a sharp contact marking the border between the granite and the deformed quartz vein relict. This vein is reduced to fractured, rounded shape quartz blocks interpenetrated by carbonates veinlets. A centimetric scale ultracataclastic layer consisting in a mix of carbonates, clays and granitic clasts marks the border with the host rock. Those observations indicate that a Ca rich fluid has circulated during the reactivation of the fracture, precipitating carbonates which were crushed due to ongoing shearing.

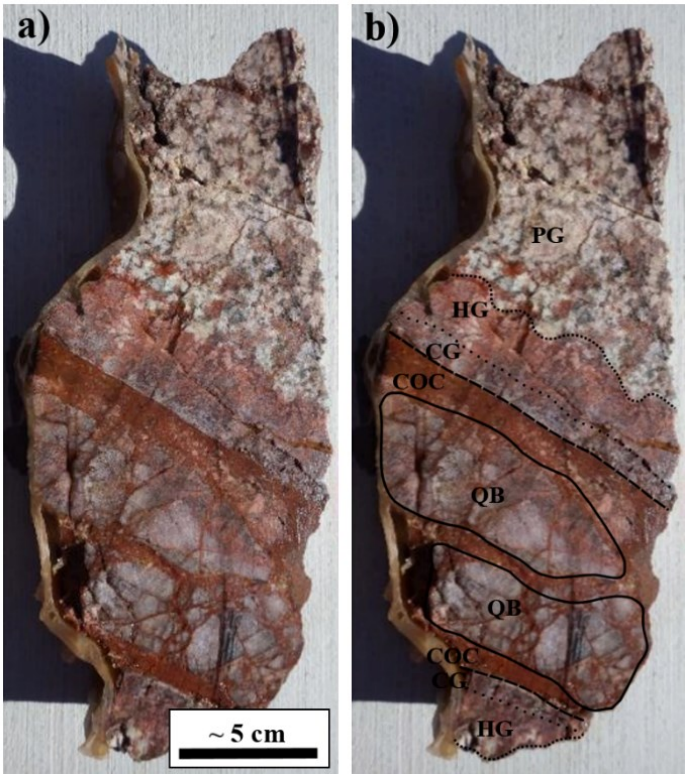


Figure 12: Pictures from zone B of a quartz vein slice from Death Valley with a) the original picture and b) the different zones characterizing the slice. QB: Quartz blocks; COC: Cataclastic oxides/clays layer; CG: Cataclased granite; HG: Hydrothermalized granite; PG: Porphyritic granite

Finally, high strain is highlighted in the zone C (Figure 7) and characterized by two meters width clay gouge. The sample from this gouge (Figure 13) presents a global matrix rich in clay minerals, mainly illite, but also some reworked clasts of quartz, carbonates and oxides. Microscopic and SEM observations show signs of intense shearing as sigma clasts. In both sides of the gouge the host rock is highly fractured and altered.



Figure 13: Picture from zone C of a sample from a clay gouge presenting signs of a high amount of dextral shear deformation

Complementary analyses are performed as SEM analyses supported by XRD and cathodoluminescence analyses to better characterize the mineralogical, structural and chemical composition of the samples. Geochemical analyses are also performed in order to better quantify the chemical composition of the bulk rock and to characterize the possible chemical elements transfer. Others analyzes are planned: 1) fluid inclusions analyses in quartz crystals in order to obtain information on the pressure, temperature and salinity of the fluid which has circulated, 2) calcimetry analyses to determine the proportion of carbonates in the samples and 3) goniometry and EBSD to investigate microfabric characteristics of fault core zones.

6. DISCUSSION AND CONCLUSION

6.1 Comparison of granite alteration between NH and SsF

The vein emplacement alteration leads to the transformation of primary minerals of the whole rock into neo-formed minerals. In both SsF and NH granite, the same primary minerals are altered. Plagioclase is transformed into illite an kaolinite or locally into tosudite in the case of SsF (Bartier et al., 2008) and biotite is transformed into chlorite (propylithic alteration) and then illite (vein alteration). Those veins are composed of different mineralization as carbonates, oxides, clays, quartz and barite and found in both granites. It shows that different generation of fluid have circulated. However, in the Noble Hills, the propylitic alteration, well described in the SsF granite, is probably almost totally overprinted by the vein alteration due to the nearly total absence of chlorite and epidote.

6.2 Impact of the deformation on fluid circulation

The reservoir productivity at SsF is mainly taken up by a few opened fractures showing incipient geodic minerals, essentially quartz precipitations (Vidal and Genter, 2018 and references therein). Glaas et al., (2019) mentioned that in geothermal system without shear deformation (opening mode), fractures filled by different mineralization are considered as paleo-permeable zones, which allow the fluid to circulate only in the walls (Figure 3). Compare to SsF, the NH granite undergone a higher amount of shear deformation due to the recent activity of the SDVFZ. By considering this deformation, some mineralized fractures can be reworked allowing the fluid to circulate in the fracture and the increase of fluid/rock interactions (Figure 12). In that case, deformation promotes fluid circulation which is mostly concentrated in the fault core. However, a high amount of deformation associated to fluid circulation can increase the fluid/rock interaction to such a way that a significant amount of clay minerals will be produced (Figure 13). As described by Glaas et al., (2019), fractures filled by clay minerals act as a barrier concentrating the fluid in the walls. This can be applied in the case of the clay gouge presenting in Figure 13, but we suggest here that the fault plugging was promoted by the shear deformation. Depending on the amount of deformation and associated to fluid circulation, fault zone behavior can be drastically modified (Wallace and Morris, 1986).

This work has shown 1) that analogue studies are important to enhance the understanding of the reservoir in its entirety and 2) through the SsF granite knowledges and the field observations in the NH, we see that both granites react similarly to this alteration. Moreover, we conclude that deformation is a crucial parameter influencing fault zone properties and which in turn modify substantially their permeability and so the geothermal exploitation potential.

To enrich the panel of possible analogues to SsF, so to granitic reservoirs and confirm our preliminary interpretations, analogues in the URG shoulders (Black Forest, Germany and Vosges Mountains, France) will come in complement to get information about the importance of the structural inheritance and how those structures influence the fluid circulation.

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REFERENCES

Bailleux, P., Schill, E., Dezayes, C., 2011. 3-D structural regional model of the EGS Soultz site (northern Upper Rhine Graben, France): insights and perspectives. Presented at the 36rd Workshop on Geothermal Reservoir Engineering, p. SGP-TR-191.

Bartier, D., Ledésert, B., Clauer, N., Meunier, A., Liewig, N., Morvan, G., Addad, A., 2008. Hydrothermal alteration of the Soultz-sous-Forêts granite (Hot Fractured Rock geothermal exchanger) into a tosudite and illite assemblage. Eur. J. Mineral. 20, 131–142. https://doi.org/10.1127/0935-1221/2008/0020-1787

Brady III, R.H., 1986. Cenozoic Geology of the Northern Avawatz Mountains in Relation to the Intersection of the Garlock and Death Valley Fault Zones, San Bernardino County, California. University of California, Davis.

Burchfiel, B.C., Stewart, J.H., 1966. "Pull-apart" origin of the central segment of Death Valley, California. GSA Bull. 77, 439–442. https://doi.org/10.1130/0016-7606(1966)77[439:POOTCS]2.0.CO;2

Butler, P.R., Troxel, B.W., Verosub, K.L., 1988. Late Cenozoic history and styles of deformation along the southern Death Valley fault zone, California. GSA Bull. 100, 402–410. https://doi.org/10.1130/0016-7606(1988)100<0402:LCHASO>2.3.CO;2

Calzia, J.P., Rämö, O.T., 2000. Late Cenozoic crustal extension and magmatism, southern Death Valley region, California. GSA Field Guid. 2, 135–164. https://doi.org/10.1130/0-8137-0002-7.135

Curewitz, D., Karson, J.A., 1997. Structural settings of hydrothermal outflow: Fracture permeability maintained by fault propagation and interaction. J. Volcanol. Geotherm. Res. 79, 149–168. https://doi.org/10.1016/S0377-0273(97)00027-9

Dezayes, C., Genter, A., Gentier, S., 2004. Fracture Network of the EGS Geothermal Reservoir at Soultz-sous-Forêts (Rhine Graben, France). Geotherm. Resour. Counc. Trans. Vol. 28, 7.

Dezayes, C., Genter, A., Valley, B., 2010. Structure of the low permeable naturally fractured geothermal reservoir at Soultz. Comptes Rendus Geosci., Vers l'exploitation des ressources géothermiques profondes des systèmes hydrothermaux convectifs en milieux naturellement fracturés 342, 517–530. https://doi.org/10.1016/j.crte.2009.10.002

Dezayes, C., Lerouge, C., 2019. Reconstructing Paleofluid Circulation at the Hercynian Basement/Mesozoic Sedimentary Cover Interface in the Upper Rhine Graben [WWW Document]. Geofluids. https://doi.org/10.1155/2019/4849860

Dèzes, P., Schmid, S.M., Ziegler, P.A., 2004. Evolution of the European Cenozoic Rift System: interaction of the Alpine and Pyrenean orogens with their foreland lithosphere. Tectonophysics 389, 1–33. https://doi.org/10.1016/j.tecto.2004.06.011

Edel, J.-B., Schulmann, K., 2009. Geophysical constraints and model of the "Saxothuringian and Rhenohercynian subductions – magmatic arc system" in NE France and SW Germany. Bull. Société Géologique Fr. 180, 545–558. https://doi.org/10.2113/gssgfbull.180.6.545

Genter, A., 1989. Géothermie roches chaudes sèches : le granite de Soultz-sous-Forêts (Bas-Rhin, France) : fracturation naturelle, altérations hydrothermales et interaction eau-roche. Université d'Orléans.

Genter, A., Traineau, H., Dezayes, C., Elsass, P., Ledésert, B., Meunier, A., Villemin, T., 1995. Fracture analysis and reservoir characterization of the granitic basement in the HRD Soultz project (France). Fract. Anal. Reserv. Charact. Granitic Basement HRD Soultz Proj. Fr. 4, 189–214.

Glaas, C., Vidal, J., Patrier, P., Girard, J.-F., Beaufort, D., Petit, S., Genter, A., 2019. How Do Secondary Minerals in Granite Help Distinguish Paleo- from Present-Day Permeable Fracture Zones? Joint Interpretation of SWIR Spectroscopy and Geophysical Logs in the Geothermal Wells of Northern Alsace [WWW Document]. Geofluids. https://doi.org/10.1155/2019/8231816

Kübler, B., 1968. La cristallinité de l'illite et les zones tout à fait supérieures du métamorphisme. Etages Tecton. 105–1021.

Ledesert, B., Berger, G., Meunier, A., Genter, A., Bouchet, A., 1999. Diagenetic-type reactions related to hydrothermal alteration in the Soultz-sous-Forets Granite, France. Eur. J. Mineral. 11, 731–741.

Machette, M.N., Johnson, M.L., Slate, J.L., Klinger, R., Machette, M., Knott, J., Sarna-wojcicki, A., Block, D.L., Budahn, J.R., Crone, A.J., Dohrenwend, J.C., Fleck, R.J., Frankel, K., 2001. Quaternary and Late Pliocene Geology of the Death Valley Region: Recent Observations on Tectonics, Stratigraphy, and Lake Cycles (Guidebook for the 2001 Pacific Cell - Friends of the Pleistocene Fieldtrip), Chapter J.

Norton, I., 2011. Two-stage formation of Death Valley. Geosphere 7, 171–182. https://doi.org/10.1130/GES00588.1

Pauwels, H., Fouillac, C., Criaud, A., 1992. Water-rock interactions during experiments within the geothermal Hot Dry Rock borehole GPK1, Soultz-sous-Foreˆts, Alsace, France. Appl. Geochem. 7, 243–255.

Pauwels, H., Fouillac, C., Fouillac, A.-M., 1993. Chemistry and isotopes of deep geothermal saline fluids in the Upper Rhine Graben: Origin of compounds and water-rock interactions. Geochim. Cosmochim. Acta 57, 2737–2749. https://doi.org/10.1016/0016-7037(93)90387-C

Pavlis, T.L., Trullenque, G., Submitted. Evidence for 40-41 km of dextral slip on the southern Death Valley fault zone: Implications for the Eastern California Shear Zone and Extensional Tectonics. Geology.

Schumacher, M.E., 2002. Upper Rhine Graben: Role of preexisting structures during rift evolution. Tectonics 21, 6–1. https://doi.org/10.1029/2001TC900022

Stewart, J.H., 1983. Extensional tectonics in the Death Valley area, California: Transport of the Panamint Range structural block 80 km northwestward. Geology 11, 153–157. https://doi.org/10.1130/0091-7613(1983)11<153:ETITDV>2.0.CO;2

Stipp, M., Stünitz, H., Heilbronner, R., Schmid, S.M., 2002. The eastern Tonale fault zone: a 'natural laboratory' for crystal plastic deformation of quartz over a temperature range from 250 to 700°C. J. Struct. Geol. 24, 1861–1884. https://doi.org/10.1016/S0191-8141(02)00035-4

Streckeisen, A., 1973. Classification and Nomenclature of Plutonic Rocks: Recommendations of the IUGS Subcommission on the Systematics of Igneous Rocks. GeoTimes 18, 26–30. https://doi.org/10.1007/BF01820841.

Traineau, H., Genter, A., Cautru, J.P., Fabriol, H., Chevremont, P., 1991. Petrography of the granite massif from drill cutting analysis and well log interpretation in the geothermal HDR borehole GPK1 (Soultz, Alsace, France). Petrogr. Granite Massif Drill Cut. Anal. Well Log Interpret. Geotherm. HDR Boreh. GPK1 Soultz Alsace Fr. 3, 1–29.

Troxel, B.W., Butler, P.R., 1979. Rate of Cenozoic Slip on Normal Faults, South-central Death Valley, California. Department of Geology, University of California.

Trullenque, G., Genter, A., Leiss, B., Wagner, B., Bouchet, R., Leoutre, E., Malnar, B., Bär, K., Rajšl, I., 2018. Upscaling of EGS in Different Geological Conditions: a European Perspective. Proc. 43rd Workshop Geotherm. Reserv. Eng. Standford Univ. Standford Calif. 10.

Vidal, J., Genter, A., 2018. Overview of naturally permeable fractured reservoirs in the central and southern Upper Rhine Graben: Insights from geothermal wells. Geothermics 74, 57–73. https://doi.org/10.1016/j.geothermics.2018.02.003

Wallace, R.E., Morris, H.T., 1986. Characteristics of faults and shear zones in deep mines. Pure Appl. Geophys. 124, 107–125. https://doi.org/10.1007/BF00875721

Wooden, J.L., Miller, D.M., 1990. Chronologic and isotopic framework for Early Proterozoic crustal evolution in the eastern Mojave Desert Region, SE California. J. Geophys. Res. Solid Earth 95, 20133–20146. https://doi.org/10.1029/JB095iB12p20133

Ziegler, P.A., 1992. European Cenozoic rift system. Tectonophysics, Geodynamics of rifting, volume 1 Case history studies on rifts: Europe and Asia 208, 91–111. https://doi.org/10.1016/0040-1951(92)90338-7