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# Seismic and Aseismic Deformation during Hydraulic Fracturing/Shearing and Circulation in Hydrothermally Altered Crystalline Basement Rock

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## ABSTRACT

After decades of research on enhanced geothermal systems (EGS), induced seismicity is still a major obstacle in the development of these engineered systems. With this study, we draw attention to a key observation of the European EGS reference project in Soultz-sous-Forêts, the relationship between hydrothermal alteration of the crystalline basement and minor to aseismic deformation in natural fractures (Meller and Ledésert, 2017). Observations show that large seismic events are limited to unaltered granite, while only small seismic events occur in the hydrothermally altered zones.

To systematically investigate hydrothermal alteration products from different zones of seismic response to hydraulic shear or fracturing, we investigate cuttings from the granitic section of the GPK1 well of the Soultz EGS site. We have selected about 120 rock samples from a depth between 2,800-3,597m in 1 to 10 m intervals with smaller intervals around the fractures that have been deformed during the 93OCT11 hydraulic stimulation. Here correlations between spectral gamma ray and temperature logs with the locations of seismic events and deformation were observed. During the 93OCT11 hydraulic stimulation of the open hole section of GPK1 well, aseismic deformation tended to preferentially develop in clay rich, high porosity – high permeability and relatively thick altered fracture zones.

Here, we summarize and detail these observations and add new observations on the behavior of induced seismicity at the FORGE and Cape Modern sites that point to similar behavior.

## 1. INTRODUCTION

In EGS, two fracture stimulation mechanisms are distinguished that may occur concurrently during the hydraulic treatment (Gischig and Preisig, 2015). During hydro-shearing which is the dominant process at the Soultz EGS site (Dentzer and Bruel, 2013), over-pressure induces slip along pre-existing fractures that are favorably oriented in the stress field for reactivation in shear. During hydro-fracturing when fluid injection is performed through packed intervals new tensile fractures are propagated from the borehole by means of a fluid pressure overcoming the tensile strength of intact rock plus the minimal principal stress. In case of a pre-existing fracture oriented normal to the minimal principal stress direction, the fracture can be opened by exceeding the latter only.

The achievements during the development of three reservoirs by more than 15 major stimulations over a 20-year period between 1988 and 2005 at enhanced geothermal systems (EGS) test site at Soultz-sous-Forêts (France) in the Upper Rhine Graben (Schill et al., 2017) have contributed significantly to the reservoir engineering of this naturally fractured system. At Soultz, EGS development comprises crystalline basement rock and extends over three reservoir levels, i.e., at 2000 m depth (at the top of the granitic basement), at 3500 m, and at 5000 m. About 15 major hydraulic and chemical stimulations were carried out to improve reservoir condition at those different levels.

In formations with very low intrinsic permeability and negligible open fracture density, EGS development primarily relies on hydrofracturing. This method is used to create localized vertical fractures along horizontal or highly deviated borehole trajectories. These engineered fractures allow for fluid flow and act as heat exchangers, enabling the conduction of heat from the surrounding rock to the injected fluids. The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) EGS site in Milford, Utah (Figure 1a), with measured permeabilities of less than 30 microdarcies was selected due to its low-permeability, conductive thermal regime (Moore et al., 2019; Niemz et al., 2024). In July 2023 and again from March to April 2024, the reservoir performance at Utah FORGE was enhanced through two multi-stage, high-pressure hydraulic stimulations along a 300-meter of granitoid rock in a highly deviated well. These stimulations successfully opened new hydraulic fractures and/or activated pre-existing natural fractures. During a 10-hour circulation test, the site achieved a production rate of >22 kg/s and an injection rate of 35 kg/s (Utah FORGE, 2024). At the Project Red site in northern Nevada, following plug-and-perf stimulation and proppant injection, well-to-well flow rates reached 63 kg/s (Norbeck and Latimer, 2023). Additionally, at Project Cape, located near the FORGE site (Figure 1a), 15 horizontal wells had been drilled and a three-well pad had been stimulated using the plug-and-perf method with proppants by September 2024. During a 30-day test, the first production well reached a maximum well-to-well flow rate of 121 kg/s, stabilizing at 93 kg/s (Norbeck et al., 2024).

At the FORGE site, detailed analyses of well 16A(78)-32 (Jones et al., 2021) revealed that the upper approximately 425 meters of the plutonic basement consists of coarse-grained, sheared rock with variable composition, including diorite, monzodiorite, quartz monzodiorite, granodiorite, quartz monzonite, and granite, with granite being the most common rock type. Brittle deformation, including brecciation, veining, and shearing, leads to the formation of cataclasite and gouge, and is more intense in the upper part of this interval (Figure 1b). Below approximately 1,540 meters, ductile deformation becomes dominant, marked by dynamic recrystallization and finely banded mylonites. Locally, brittle deformation overprints older ductile structures, with mylonite clasts being incorporated into the cataclasite. Secondary mineral abundances decrease with depth, from 14 wt% at the top of the sheared coarse-grained plutonic rock to 2 wt% at 1,675 meters. Primary phases are altered into clay minerals (kaolinite, smectite, illite, and chlorite) and carbonate (Figure 1c). Hematite staining also diminishes with depth, moving away from the basement contact. Between 1,400 and 1,525 meters, propylitic alteration occurs, with open-space filling of epidote ± actinolite, later cut by carbonate veins. Carbonates, including siderite, dolomite, and calcite, are the most common minerals filling these open spaces. This interval of sheared rock is interpreted to have formed through normal faulting during Basin and Range extension. The modern low-angle dip of approximately 25-30° to the west of the top of the crystalline basement is thought to result from the rotation of the footwall block (Bartley, 2019). During four circulation experiments at FORGE, it was shown that the wells 16A(78)-32 and 16B(78)-32 were successfully connected via the fracture network that was created during the 2022 stimulation treatments (Niemz et al., 2025).

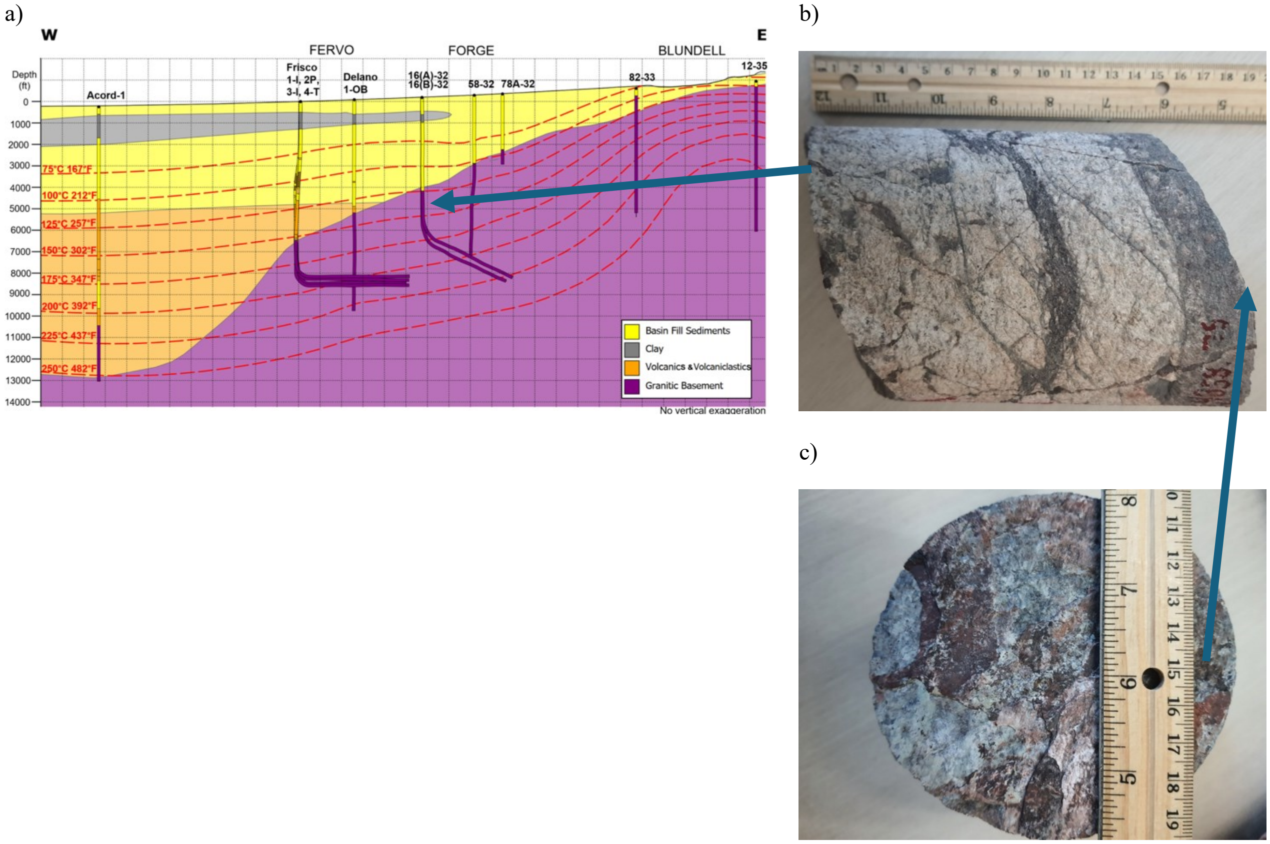

**Figure 1: a) The location of the representative core sample from the sheared interval b) sideview and c) bottom view is indicated along the borehole outline at depth (modified from Fercho et al., 2024). The sample was taken from a depth of 1,480.79-1,480.95 m from the well 16B(78)-35.**

In this study, we focus on the hydraulic stimulation 93OCT11 that extended over the borehole section from 2,800 to 3,500m in GPK1. In the Soultz-sous-Forêts wells, at 2,800m depth, the standard monzogranite (Genter, 1989) composed of plagioclase (39.9%), K-feldspar (18.8%), quartz (28.4%), biotite (8.4%), and amphibole (4.5%) turns into a second facies more intensely affected by vein alteration. The last about 100m of the selected section is characterized by a biotite and amphibole-rich granite. The zones of vein alteration are characterized by a strong modification of the primary minerals of the granite (Bartier et al., 2008; Ledésert et al., 1999, 2010; Meller et al., 2014) and are 1 to 20 m thick (Dezayes et al., 2005). They show a replacement of plagioclase, biotite, and amphibole by clay minerals such as mostly illite, and tosudite (a Li-bearing clay) in rare zones of the granite (Bartier et al., 2008; Ledésert et al., 1999). Quartz is sometimes totally dissolved (Vidal et al., 2016). The porosity of the altered fracture walls can reach 20% (Ledésert et al., 1999), and the initial texture of the granite can be lost. Newly formed minerals, such as calcite or clay minerals, are also found in veinlets crosscutting the granite (Dubois et al., 2000) and can be used to characterize paleo-flow pathways (Ledésert et al., 2009). Locally, cm-thick secondary quartz veins took place within such hydrothermal altered and fractured zones.

During injection, approximately 95% of the flow entered the rock mass through just ten major flowing fractures, most of which were naturally permeable (Evans et al., 2005). Following the injection process, the transmissivity of the section above the fault increased by a factor of 200, and the number of permeable fractures rose to about 100. The distribution of these fractures was clearly organized, with major flowing fractures surrounded by clusters of weakly-flowing, newly permeabilized fractures. These newly created or enhanced permeability zones closely correlate with areas of hydrothermal alteration, which, in turn, are associated with the intersection of the borehole and extensive, hydrothermally altered, cataclastic shear structures. These zones display a fracture cluster organization, with various types of sealed fractures, including post-filled joints, sheared fractures, and veins. Within the permeable zones, the main hydrothermal deposits include geodic quartz, carbonates, illite, and, more locally, sulfides. The fracture wall rocks are extensively altered, with processes such as the dissolution of igneous minerals, the crystallization of new minerals, and an increase in both porosity and permeability (Ledésert et al., 2010).

## 2. INDUCED SEISMICITY AND DEFORMATION

During the 93OCT11 hydraulic stimulation of the open-hole section of the GPK1 well, a total of 44,000 m³ of fluid was injected. Borehole observations indicate that shearing and permeability enhancement are predominantly confined to hydrothermally altered rock zones associated with cataclastic shear structures. This suggests that most microseismic activity represents fluid penetration along these structures, which act as primary flow paths for fluids in the rock mass under natural conditions. As a result, permeability enhancement is largely limited to these shear zones, with minimal enhancement occurring in the surrounding rock blocks (Evans et al., 2005).

Induced seismicity was monitored using both downhole and surface seismic networks, with approximately 20,000 seismic events recorded by the downhole sensors and 165 events by the surface network. The largest observed magnitude was 1.9. Borehole televiewer observations revealed some slip events exceeding 4 cm at the borehole wall, a displacement much larger than that typically associated with microseismic events of comparable magnitude (Cornet et al., 1997). These larger slip events were likely aseismic, implying that induced seismicity may not be a reliable indicator of hydraulic stimulation efficiency. Instead, it primarily serves to identify zones of high pore pressure during fluid injection.

Meller and Kohl (2014) have summarized the relation between seismic and aseismic slip and synthetic clay content logs during stimulation in the well GPK1 between 2,800 and 3,500 m identified by Cornet et al. (1997) and Evans et al. (2005). Major flow zones are surrounded by zones of high clay content. Slip is restricted to hydrothermally altered clay zones with high clay content observed in the synthetic logs. The occurrence of aseismic slips is restricted to clay-rich flowing faults.

Induced seismicity at both the FORGE and Cape Modern sites in Utah develops primarily in the vertical direction over time, but the characteristics of this seismic activity vary between the two locations (Figure 2). At the Cape Modern site, seismic events primarily propagate downwards from the horizontal wells, suggesting that fluid injection is inducing movement and pressure changes in the lower portions of the reservoir. In contrast, at the adjacent Utah FORGE site, induced seismicity generally occurs upwards from the injection intervals, which is indicative of fluid migration and pressure buildup within the reservoir, potentially enhancing permeability in the upper regions.

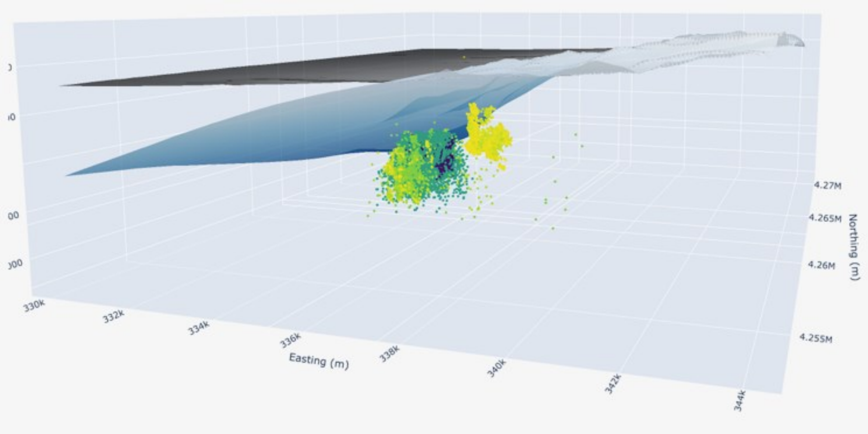

**Figure 2: Induced seismicity at the Utah FORGE and Cape Modern site underneath the top of the granitic basement rock between Feb (blue) to Aug (yellow) 2024 (Nakata, unpublished).**

In both sites, seismic events are concentrated within a specific depth band, approximately 2,000 meters below the top of the granitic basement. Notably, these seismic events are confined to this depth range and do not extend into the sheared interval. The sheared zone, which represents a region of intense hydrothermal alteration and cataclastic shear structures, appears to act as a barrier to further propagation of seismicity. This suggests that the structural and mineralogical characteristics of the sheared zone may limit the vertical extent of seismic events, preventing them from penetrating deeper into the basement rock.

The concentration of seismicity within this depth range is consistent with the geological setting in the area. Understanding these patterns is crucial for assessing reservoir. The observations at both FORGE and Cape Modern underscore the importance of monitoring seismicity and understanding the geological characteristics that control fluid migration and stress distribution in the reservoir.

## 3. HYDROTHERMAL ALTERATION AT THE SOULTZ EGS SITE

At the Soultz EGS site we distinguish two types of hydrothermal alteration:

(1) **Propylitic alteration** (Figure 3) occurred towards the end of the granite body's crystallization. This weak alteration is characterized by the partial replacement of biotite and hornblende with chlorite, plagioclase with illite and corrensite, and the formation of epidote and hydrogarnet within the rock (Genter, 1989; Ledésert, 1993; Ledésert et al., 1996, 1999). This alteration is of limited relevance to EGS because it minimally affects the mineralogy or porosity of the rock. Generally small-scale fractures filled with carbonates are associated with propylitic alteration.

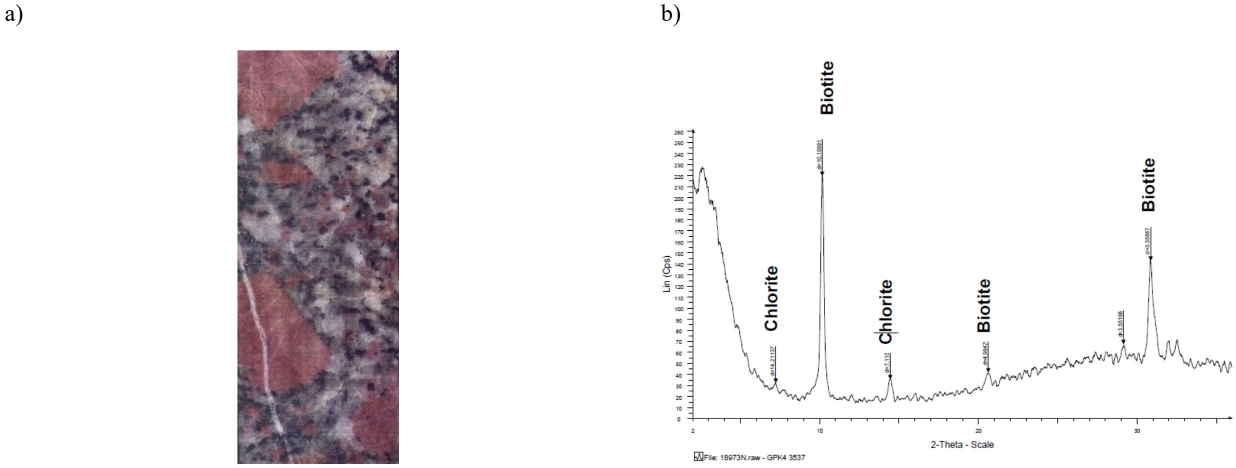

**Figure 3: a) Example of a porphyritic monzogranite sample with a small-scale fracture filled with calcite affected by propylitic alteration at 1667 m from the EPS1 Soultz well and b) Example of X-ray diffraction pattern for a propylitic granite facies in GPK4 well at Soultz showing the primary biotite and the secondary chlorite (depth 3537 m, untreated sample from Dezayes et al., 2005).**

(2) **Vein alteration** (Figure 4), found along fractures, results from the interaction between the rock and natural fluids that have flowed through the fracture network, some of which may still be active (Pauwels et al., 1993). This alteration is of greater significance as it can influence fluid flow and mineral deposition within the reservoir. Genter et al. (1995) have shown that the width of alteration zones on both sides of the fractures ranges between 0.2 and 28.5 m with an average of 3 m.

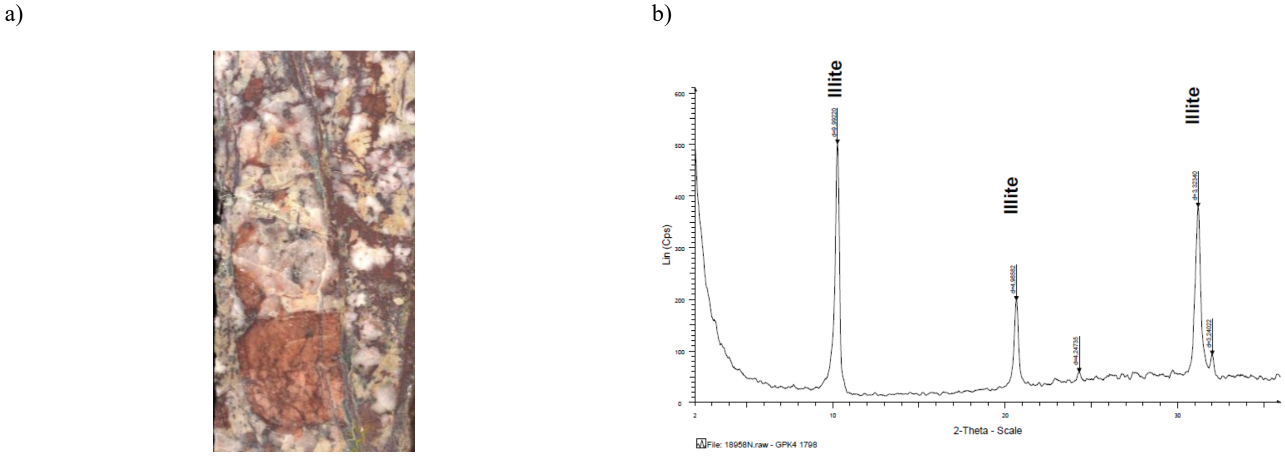

**Figure 4: a) Example of a hydrothermally altered and fractured granite sample from the GPK-1 Soultz well at 1375 m showing a nearly vertical sealed fracture, brittle deformation and wall rock effect and b) Example of X-ray diffraction pattern for a vein alteration granite facies in GPK-4 well at Soultz showing secondary illite (depth 1798 m, untreated sample from Dezayes et al., 2005).**

Within hydrothermally altered and fractured zones, natural fractures are closely spaced exhibiting a cluster organization. In the core of such zone, cataclastic facies like breccia, microbreccia even protomylonite are observed (Genter, 1989). They correspond to paleo-shearing movements related to the tectonic history of the Upper Rhine Graben due to successive compressive and extensional paleo-stress episodes. Around the fault core where the displacement is maximal, a wall-rock effect is visible on the granite is visible. It is characterized by the dissolution of primary biotite and plagioclase and the precipitation of illite. High porosity values are associated to such wall-rocks where natural fracture density is low. Finally, such zones are characterized by the precipitation of later drusy quartz veins suggesting dilatational stresses. Such features are generally associated to present permeable features (Vidal et al., 2019).

Vein alteration significantly modifies the properties of the granite, leading to a decrease in density while greatly increasing both porosity and P-wave velocity (Ledésert et al., 1993a). The mineralogy is locally transformed, with complete dissolution of quartz, plagioclase, biotite, and hornblende, leaving only K-feldspar preserved. Several studies have shown that this alteration results from the interaction between the granitic basement and fluids of sedimentary origin, as evidenced by the Cl/Br ratio, the chemistry and bulk chlorinity of the reservoir fluids (Pauwels et al., 1993), and the presence of organic matter (Ledésert et al., 1996).

Illite is a common alteration mineral found in the Soultz granite (Genter et al., 1995; Bartier et al., 2008). Detailed mineralogical studies of core samples have established a strong association between fracture zones and high illite content (Genter et al., 1995). Illite precipitates as needles up to 20 mm long (Bartier et al., 2008; Ledésert, 1993) or as flakes, either as alteration products of igneous minerals (e.g., biotite, oligoclase) or within veinlets. While illite has a minimal effect on porosity reduction, it can significantly decrease permeability, as demonstrated in studies of oil reservoirs (Hamilton et al., 1989; Wilkinson and Haszeldine, 2002). In highly altered and fractured granite of the Soultz EGS site, the illite content was estimated to be around 35 wt.% based on bulk rock chemical analysis (Genter, 1989). In these zones, illite was the main secondary clay mineral associated with vein alteration. Locally, other clay minerals like illite/smectite, tosudite, smectite, and kaolinite were observed based on XRD measurements on core samples at Soultz (Genter, 1989; Dezayes et al., 2004).

Grain-size fractions of altered granite and argillite vein samples show mixtures of 2M1 and 1M illite polytypes (Schleicher et al., 2006). The 2M1 illite predominates in vein fillings, while the fibrous 1M illite is more common in the granite matrix. Multiple fluid injection phases into the granite formed distinct illite assemblages, each reflecting different crystal growth events. K–Ar dating and crystallite thickness analysis suggest that the argillite veins initially formed in the Permian, with subsequent illite crystallization occurring during the Jurassic and Cretaceous periods. Fluid chemistry variations and fluid–rock interaction influenced the illite structure and composition as the granite progressively sealed during episodic hydrothermal activity after the Variscan orogeny.

Locally, Li-enriched fluids facilitated the crystallization of tosudite (Ledesert et al., 1996, 1999; Bartier et al., 2008). In tosudite-bearing zones, illite and quartz precipitated as a result of the dissolution of tosudite and biotite. Tosudite crystallization occurred at temperatures of approximately 350–400°C, followed by the precipitation of quartz, carbonates, and illite at around 140°C (Ledesert et al., 1999), similar to the temperatures of current natural fluids (Pauwels et al., 1993; Dubois et al., 1996). In these zones, tosudite replaces plagioclase and exhibits a characteristic honeycomb structure, which contributes to the 25% porosity of the altered rock. Despite its effect on porosity and potential permeability enhancement, tosudite is not considered a major secondary mineral within the Soultz granite due to its relative scarcity.

Geochemical calculations (Pauwels et al., 1993; Komninou and Yardley, 1997) indicate that carbonates and quartz continue to precipitate from natural fluids, reducing the bulk porosity of granite as they accumulate within fracture planes (Ledesert et al., 2009). Rabemanana et al. (2003) demonstrated that calcite precipitation dominates over quartz precipitation in natural environments, and that quartz reactions have minimal impact on the reservoir's characteristics.

The goal of this study is the systematic characterization of the clay minerals occurring in the vein alteration zones. We have collected 120 samples from the cuttings of the GPK1 well along the section between 2,800 and 3,597m depth (Figure 5). In a first step the samples have been separated by grain size into the fractions <53 μm, >53 μm and <106 μm, > 106 μm and < 300 μm, >300 μm and <1 mm to analyze the general mineral content. A preliminary spectral analysis of the <53 μm suggests the presence of albite in both samples. Additionally, the sample from 3,093 m appears to contain phlogopite (biotite), chlorite and illite, based on the spectral signatures observed.

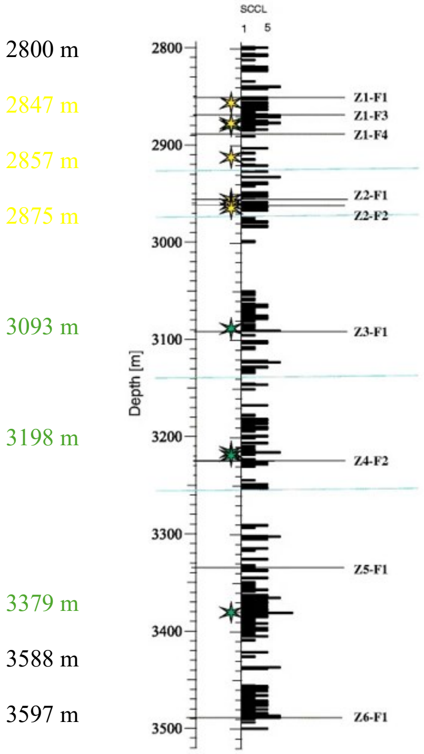

**Figure 5: a) Synthetic clay content log (modified from Meller and Kohl, 2014) compared to the borehole sections with seismic slip (green stars) and aseismic slip (yellow stars) and the depth from which first XRD spectra have been obtained.**

## 4. OUTLOOK

The initial XRD results appear to align with findings from previous studies conducted at the Soultz EGS site. To build on these findings, the next phase of the study will involve isolating the clay fraction from the cuttings by gravity in deionized water. This fraction will then be analyzed at low 2-theta angles (2° to 35°) under both air-dried and glycolated conditions to further refine the mineralogical identification and assess any potential changes in the clay content. This approach will provide deeper insights into the mineralogical composition and evolution of the reservoir.

Initial findings from the Utah FORGE site suggest that induced seismicity is significantly reduced within the hydrothermally altered, sheared interval at the top of the granite. This observation prompts further investigation into the spatial distribution and temporal development of induced seismicity. To improve the accuracy of these findings and enhance our understanding of seismicity evolution, we plan to re-locate the seismic events with greater precision and refine the geological model accordingly.

As part of this effort, XRD analysis will be conducted on the clay fraction extracted from fracture fillings within a core section of well 16B(78)-35, specifically between depths of 1,480.79 m and 1,480.95 m. This analysis will help identify the mineralogical composition of the fracture-fill material, providing insights into the geomechanical properties of the altered zone and its influence on induced seismicity. By integrating these data with seismic event relocations, we aim to better understand the role of hydrothermal alteration in the control of seismic behavior at the site and refine our approach to reservoir stimulation.

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