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# Clay minerals related to the circulation of geothermal fluids in boreholes at Rittershoffen (Alsace, France)

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ABSTRACT

Two geothermal wells, GRT-1 and GRT-2, were drilled into the granite at Rittershoffen (Alsace, France) in the Upper Rhine Graben to exploit geothermal resources at the sediment-basement interface. Brine circulation occurs in a permeable fracture network and leads to hydrothermal alteration of the host rocks. The goal of the study was to characterize the petrography and mineralogy of the altered rocks with respect to the permeable fracture zones in the granitic basement. As clay minerals are highly reactive to hydrothermal alteration, they can be used as indicators of present-day and paleo-circulation systems. Special attention has been paid to the textural, structural and chemical properties of these minerals. The fine-grained clay fraction (<5 μm) was analyzed around the originally permeable fracture zones to observe the crystal structure of clay minerals using X-ray diffraction. Chemical microanalysis of the clay minerals was performed using scanning electron microscopy coupled with energy dispersive X-ray spectroscopy. The occurrences of mixed layers illite-smectite (~10% smectite) provide a promising guide for identifying the fracture zones that control the present-day circulation of geothermal fluids in the Rittershoffen wells. However, multistage paleo-circulation systems could lead to an abundance of heterogeneous and fine-grained illitic minerals that could plug the fracture system. The permeability of fracture zones in the GRT-1 well was likely reduced because of an intense illitization, and the well was stimulated. The occurrence of chlorite in the permeable fracture zones of GRT-2 is indicative of less intense illitization, and the natural permeability is much higher in GRT-2 than in GRT-1.
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## 1. Introduction

In geothermal systems, alteration minerals provide useful information about the physico-chemical conditions of both past and present hydrothermal activity. This is particularly the case with clay minerals, which have been investigated as markers of circulation zones based on their reactivity to changes in physico-chemical conditions (Beaufort et al., 1992, 1996; Browne and Ellis, 1970; Flexser, 1991; Mas et al., 2006; Patrier et al., 1996; Reyes, 1990). The properties of clay minerals are affected by temperature in addition to several other factors, such as rock and fluid chemistries, time and the fluid/rock ratio. This study focused on the argillic alteration of permeable fracture zones related to a hydrothermal system located in the Upper Rhine Graben at Rittershoffen in France (Fig. 1). Two deep geothermal wells - GRT-1, which has a vertical trajectory, and GRT-2, which has a deviated trajectory - intersect natural, permeable fracture zones in the sandstones and granitic basement beneath Rittershoffen (Baujard et al., 2017; Vidal et al., 2017). The influence of argillic alteration on the permeability of fracture zones at the borehole scale is an important milestone for an industrial project because fracture zones channel hot geothermal fluids that are exploited for high-temperature (>160 °C) heat applications at the surface.

Geothermal systems are dynamic systems that are constantly evolving; thus, the observed secondary minerals potentially consist of several superimposed alteration assemblages. In Rittershoffen boreholes, the mineral products of the existing hydrothermal circulation system (160 °C) appear to be superimposed upon previous secondary minerals formed during earlier circulations events. Abundance of secondary minerals may lead to plugging and the transformation of fracture zones from conduits into barriers to fluid flow. As the nature of fracture permeability is an important aspect of this geothermal project, most of the cutting samples were collected along the open-hole sections of wells around the originally permeable (OP) fracture zones in both wells. Cutting samples from both GRT-1 and GRT-2 were investigated to identify the alteration mineralogies, and special attention was paid

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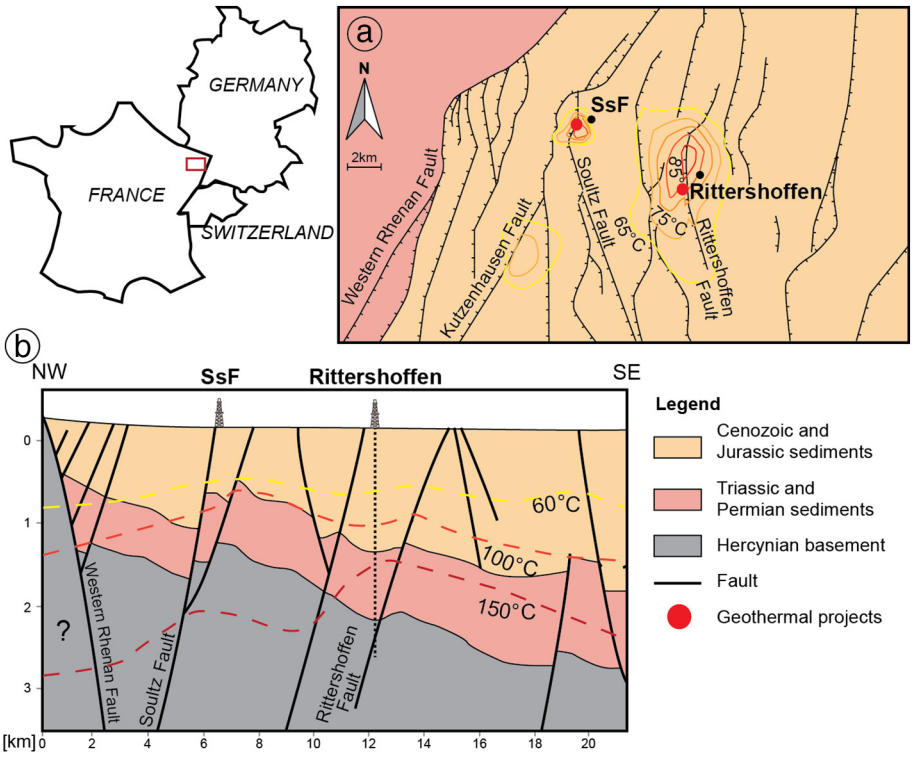


**Fig. 1.** Location of the Rittershoffen geothermal site. a) Geological and structural map of the Rittershoffen and Soultz-sous-Forêts (SsF) area. Isotherms at the top of the basement are from Baillieux et al. (2014). b) Geological cross section through the Rittershoffen and Soultz-sous-Forêts geothermal sites after *Geoportail of EU-Project GeORG - INTERREG IV Upper Rhine* (2012). The dashed line is an interpreted trajectory of the geothermal well GRT-1.

to the clay fraction. The fine-grained fraction of cuttings (<5 μm) was analyzed using X-ray Diffraction (XRD) to identify well-crystallized illite, poorly crystallized illite and mixed layers illite-smectite. Then, scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS) was used to analyze the chemical compositions of the clay minerals.

## 2. Geological context

The geothermal site at Rittershoffen is located in the Upper Rhine Graben (URG), approximately 15 km east of the Western Rhenan fault and less than 10 km from the well-known Soultz-sous-Forêts geothermal site (Alsace, France) (Fig. 1a). In the URG, the underground temperature distribution is spatially heterogeneous, and several geothermal anomalies are concentrated throughout the western side of the URG in the areas of Soultz-sous-Forêts and Rittershoffen (Baillieux et al., 2013; Pribnow and Schellschmidt, 2000; Schellschmidt and Clauser, 1996). Temperature anomalies at the top of the granitic basement indicated by several temperature measurements are concentrated along the Soultz and Kutzenhausen normal faults that dip toward the west (Fig. 1a) (Baillieux et al., 2014). These zones are attributed to the upwelling of hot geothermal fluids through fault zones within the crystalline basement and Triassic and Permian sandstones (Fig. 1b) (Benderitter et al., 1995; Pribnow and Clauser, 2000; Pribnow and Schellschmidt, 2000). Geothermal reservoirs in the granitic basement at Rittershoffen are quite similar to the reservoir at Soultz. Both deep fluids are of the NaCl type with total dissolved solids (TDS) values close to 100 g/L (Table 1) (Sanjuan et al., 2014, 2016). The pH values of the fluids in both reservoirs are close to 5.0. The fluids are interpreted as having originated from the mixing of primary marine brine with water of meteoric origin (Sanjuan et al., 2010, 2016). The estimated temperature of the deep reservoir calculated by primary cationic geothermometers (Na-K, Na-K-Ca, Na-K-Ca-Mg, K-Mg, Na-Li and Mg-Li) and by a $\delta^{18}O_{H2O\text{-}SO4}$ isotope geothermometer was 225 ± 25 °C at Soultz and at Rittershoffen (Sanjuan et al., 2016).

Alteration episodes of the granitic reservoir are well known to have occurred in deep wells at Soultz (Genter, 1989; Hooijkaas et al., 2006; Ledésert et al., 1999; Traineau et al., 1992). Early propylitic alteration of the whole granitic batholith is characterized by the formation of epidote, the partial transformation of primary biotite into Fe,Mg-chlorite

**Table 1**
Chemical compositions of geothermal fluid sampled in the Paleozoic granite at Soultz-sous-Forêts in the well GPK-2 at a measured depth of 5000 m (Sanjuan et al., 2014) and at Rittershoffen in the well GRT-1 at a measured depth of 2580 m (Sanjuan et al., 2016).

| Location | $T_{Bottom}$ °C | pH | TDS g/L | Na mg/L | K mg/L | Ca mg/L | Mg mg/L | Cl mg/L | $SO_4$ mg/L | $SiO_2$ mg/L | Br mg/L | Li mg/L | Gas |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Soultz-sous-Forêts | 200 | 4.98 | 99 | 28,140 | 3195 | 7225 | 131 | 58,559 | 157 | 201 | 216 | 173 | $CO_2$ $N_2$ $CH_4$ |
| Rittershoffen | >160 | 6.27 | 101 | 28,451 | 3789 | 7200 | 138 | 59,900 | 220 | 146 | 251 | 190 | unknown |

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