Hydrothermal alteration of Soultz-sous-Forêts granite near the granite-sediment interface in geothermal context

Girard-Berthet V.[1], Vidal J.[1*], Whitechurch H.[1], Ulrich M.[1], Genter A.[2], Schmittbuhl J.[1]

*Correspondence: j.vidal@unistra.fr
[1] EOST, University of Strasbourg, 5 rue René Descartes, 67000 Strasbourg, France
[2] ES-Géothermie, 3A chemin du gaz, 67500 Haguenau, France

The cover-basement interface is an important issue for the geothermal resource in the Rhine Graben. Geothermal drilling such as those in Soultz-sous-Forêts (Bas-Rhin) revealed the presence of numerous fractures in granite and in its Triassic sedimentary cover filled by secondary minerals. Most studies on the alteration of the granite have been conducted between 2 and 5 km deep. Few studies have been conducted on the top of the granite near the basement-sediment interface at 1.5km. However, the flow of brine through the network of fractures in the upper part of the granite reservoir caused successive penetrative mineralogical transformations. Therefore, this study focused on alteration products over the first 200 meters of highly altered granite. 40 core samples were studied using different methods: optical microscopy, X-ray diffraction, SEM, electron microprobe, major and trace element chemical analysis. The petrographic and mineralogical study, revealed the presence of secondary minerals of varied composition within and around the fractures (Figure 1). Indeed, carbonates (calcite, dolomite, ankerite, witherite), sulfates (barite), phosphates (monazite, apatite), and clays (illite, hydromuscovite) represent the main identified minerals (Table 1).

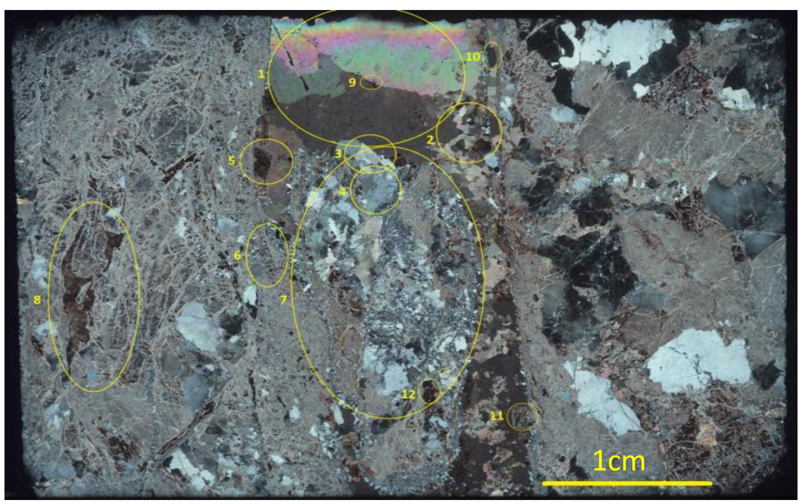

Figure 1 Photography of a thin section into the hydrothermally altered granitye at 1427.99 m observed at the petrographic microscope with a polarizer filter. Yellow circles indicate the zones measured with the SEM.

Some of these minerals, such as the secondary monazite, apatite and surprisingly illite carry radionuclides and help make the roof of the base a more radiogenic zone (seen on the gamma-ray profile) and therefore likely to provide a greater heat flow at the top basement. Gresens method (Potdevin, 1993) to estimate the transfers of major chemical elements during the weathering process has been implemented by comparing a healthy granite samples with weathered ones taken from the roof just under the sedimentary cover. The mass balances between healthy and weathered granite show that elements such as MnO, K2O, MgO and CaO, Ba, As, La are enriched in the weathered granite, whereas elements such as SiO2, Al2O3, Na2O, TiO2, P2O5, Sr, Th, U are leached.

Lame no	Numéros de la zone	Observations
10	1	- Carbonate dans carbonate (≠composition) du Ca, Mg au Fe en petit - Petite baguette sidérite (Fe) - Phosphate de terre rare (Th, La, Ce…) dans quartz - Phosphate de Al, Sr - Petite hydro-muscovite - Gypse, Mg, Ca, Mn - Dolomie entouré de carbonate, dans dolomie barytine, avec de la silice en bordure - Petit grain de S, Ca - Oxyde de fer Barytine
10	2	- Oxyde de fer - Carbonate de fer - Quartz, dolomie, micas blanc - Zircon, rutile (min primaire) - Apatite - Monazite
	3	- Quartz, mica sans Fe ou peu - Phosphate d'Al, terre rare - Monazite déstabilisée
	4	- Dolomie, quartz - Micas blanc - Potassium
	5	- Silice en bordure des silicates - Dolomie avec oxyde de fer - 2 générations : 1) Ca riche en Fe (baguette, clivage). 2) Quartz, autour dolomie : barytine, gypse
	6	- Petit filons - Micas, quartz - Phosphate Al (secondaire) - Petit min blanc avec As (associé au min secondaires) couronne autour - Un peu de Fe, Th - Rutile associé à la monazite
	7	- Calcite, trace albite - argile, quartz, Fe, éolite - Filon de mica - Zircon - Association Quartz, mica blanc, albite et carbonate
	8	- Dolomie, micas, - K-feldspath, plagioclase potassique mangé et un peu de silice - Carbonate (plusieurs générations) - Presque rien de la paragénèse original
	9	- Sulphate de calcium (petit grain)
	10	- Phosphate
	11	- Carbonate (calcite)

Table 1 List of the results measured with the SEM for each zones selected on the thin section from Figure 1

Baldeyrou (2003) has been shown experimentally and by thermodynamic modelling that the precipitation of secondary phases in Soultz-sous Forests depends on the temperature as a first order parameter and the composition of the fluid (XCO2, alkalinity of the solution, pH, content of K, Ba, P, U, Th). Indeed, the secondary minerals such as carbonates (dolomite, ankerite), hematite, quartz, illite, apatite, baryte, witherite and monazite have a similar range of crystallization between 150 and 200 °C.

The presence of albite and hydromuscovite in combination with quartz at the edges of hydrothermal veins indicate higher crystallization temperatures. Indeed, albite crystallized in the presence of quartz in minimum temperatures of about 200 - 250 ° C and hydromuscovite of the order of 250 °C, while in the center of the veins, carbonates and clays precipitate at lower temperatures between 150 and 200 °C. These temperature differences, if confirmed by a study of fluid inclusions in quartz and carbonates, would suggest different fluid pulses with different compositions and temperatures.

Nevertheless, fluids that would flow within the first 200m in the granites would have the same temperature that the temperature deduced from mineralogy and fluid inclusions from the samples between 2 and 4km depth (between 150 and 250°C ; Ledésert et al, 1999 ; Cathelineau and Boiron, 2010, Dezayes et al., 2013). Maintaining a high temperature to sediment-granite contact could be related to the concentration of radioactive elements in the upper part of the granite. These radioactive elements could be responsible for producing more heat at the basement-sediment interface, maintaining convective circuits of fluids from depth into the overlying sedimentary pile.

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