Contribution of the geothermal deep boreholes of the Soultz-sous-Forêts to the understanding of the reservoir and its exploitation

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The European experimental project of Soultz was initiated in 1984 (Gérard *et al.*, 1984) with the oil and gas crisis which was allow to develop renewable energy and new exploitation concepts. The pilot plant aims to exploit the potential energy of the deep fractured granite to produce electricity. Based on this site, 30 years of research have permitted to better understand the deep geothermal system and gradually evolve the deep geothermal conceptual model.

The site is located at Soultz-sous-Forêts, in the north-eastern part of France (Alsace), within the Tertiary Rhine Graben. An intense thermal anomaly was known in this area since long time based on an oil exploration (Hass & Hoffmann, 1929). However, geological data available concerned the sedimentary part of the basin only whereas the aim of the project was to explore the deep-seated Paleozoic granitic basement.

On the Soultz site, five boreholes have been drilled since 1987. EPS1 were fully cored to depths of 2200 m and constitutes a reference well for the geological knowledge. Two relatively shallow boreholes, called GPK1 and GPK2 were drilled to depth of 3600 m and constitute the first doublet, which demonstrated successfully a fluid circulation in a fractured rock in 1997. Three deep wells called GPK2 (deepened), GPK3 and GPK4 were drilled to depths of approximately 5000 m, where temperatures reach 200°C, necessary to produce electricity at this time with the previous power plant performance (Baumgärtner et al., 2004). All are drilled in destructive mode, but well-logs and drill cuttings are available.

EPS1 was continuous cored from 930m to the bottom hole at 2227m depth and provided lot of scientific data still being studied (Traineau *et al.*, 1991; Genter & Traineau, 1992; …Villeneuve et al., 2018). Theses cores, drill cuttings and various logs from the other well show that the granite basement is reached at around 1400m overlaid by Mesozoic and Cenozoic sediments. The granite is a massive porphyritic granite that shows some paleo-weathering at its top. Between 2700 and 3200m depth, the same granite is highly fractured and hydrothermally altered. Below this zone, the granite is less fractured and is very rich in biotite and amphibole. Starting at 4700m depth is a younger, fine-grained, two-mica and amphibole-rich granite that intrudes into the porphyritic granite (Figure, Hooijkaas et al., 2006).

Analysis of fracture network based on EPS1 cores and image logs shows that the Soultz reservoir is constituted by an interconnected permeable fracture network within an impermeable granitic rock mass, whereas it was considered as a homogeneous rock mass at the beginning of the project. This network presents two scales of fractures in relation to the tectonic history of the Paleozoic granite: the meso-fractures and the fracture zones developing hydrothermal alteration (Genter *et al.*, 2000). All are highly dipping and rather all directions are represented, whereas the main set is between N160°E and N50°E. Fractures are organized within clusters as well as fractures zones, which show three clusters along the wells (Figure, Dezayes *et al.*, 2010).

In 1997, the first circulation tests have been performed during four months between GPK1 and GPK2, 450m apart at 2900m to 3500m depth producing about 10 MW thermal. Tracers have been injected during the circulation tests and the analysis shown that the reservoir volume, in which the tracer was disperse, could been estimated of the order of more than 1 million m^3 (Aquilina *et al.*, 1998). During this circulation test, only 30% of the fluid injected into the system has been recovered and as production and injection flow was maintained in complete balance, this indicates that the Soultz system is open. Then, geothermal brines appear in the deep granite in contrary to what it was though at the beginning of the project. In July 2005, a 6 months circulation test has been running between GPK3 (injection) and GPK2-GPK4 (production) in order to characterize the system at deepest part

(5km depth). During this test, organic tracers are injected in order to contribute to the knowledge of the fluid pathways within the granitic reservoir (Sanjuan *et al.*, 2004).

Based on the geological model of fracture network, a 3D flow modelling has been performed and for the first time reproduce the tracer curve obtained during the deep circulation between the three wells GPK2, GPK3, GPK4. This model shows that the N-S striking fracture set constitutes the shortest paths between GPK3 and GPK2 while the longer paths are due to the NE-SW and NW-SE fracture sets (Figure). The circulation between GPK3 and GPK4 is totally different and show long paths mainly due to the NE-SW and NW-SE fracture sets (Figure, Gentier *et al.*, 2010).

Around the wells, the hydraulic stimulation tests have permitted to increase the permeability. Mechanical modelling based on the knowledge of fracture zones cross-cutting the wells, shown that the process is mainly due by hydroshearing acting on pre-existing fractures. Then, some irreversible openings have been created by dilation within the fractures (Gentier *et al.*, 2005). Chemical stimulation tests have also been done based on the knowledge of the filling of fractures (Schindler *et al.*, 2010).

Then a first binary plant has been erected in 2008 able to produce 1.5MWe by using a line shaft submersible pump for producing industrial flow rate. Due to severe corrosion issues related to the composition of the natural fluids, the first plant was dismantled between 2014 and 2015. Then, a new binary plant has been built able to resist those drastic corrosive fluid conditions. The new plant has an installed capacity of 1.7MWe and is producing with an availability higher than 90%.

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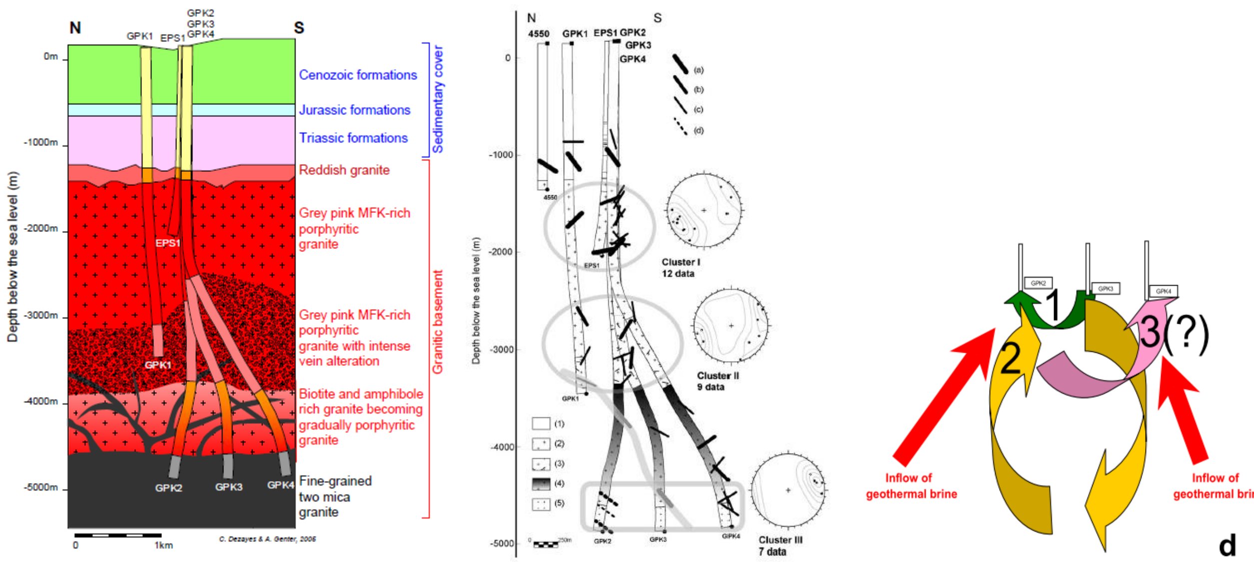

Figure: Geological conceptual model of the Soultz granite (left). Fracture zones cross-cut in the wells (center). Conceptual model of fluid circulation in the Soultz geothermal reservoir (Sanjuan *et al.*, 2006) (right).