Geothermal implications for fracture-filling hydrothermal precipitation.

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Introduction

Fluid circulation in geothermal reservoirs is greatly dependent on the geometry and hydraulic properties of fractures. The Soultz-sous-Forêts site located in the Upper Rhine Graben in Alsace, France, consists of a granitic reservoir overlain by a 1.4 km-thick sedimentary succession. This is a site of significant geothermal potential thanks to the high thermal gradient in the first 1km and the abundance of natural brines.These brines circulate overseveral kilometres,facilitating heat transfer. Exploiting this natural heat source involves using deep wells, the fracture network in the Triassic sediments and granitic basement acting as a heat exchanger. Temperature profiles show that in the sediments, the main regime for heat transfer is conductive as opposed to the convective regime in the base rock below. This makes the interface between the two a zone of particular interest with regards to fluid flow.

Core analysis and borehole wall imagery collected from reconnaissance well EPS1, drilled to a depth of 2230m, reveal an extensive fracture network throughout the granite and overlying sediments, including both open fractures and fractures filled through mineral precipitation (primarily quartz, barite, calcite, and galena). These fractures have a preferred orientation; the two major fracture sets strike N005° and N170°, dipping 70°W and 70°E respectively. Here we present an experimental study that aims to provide insights into the impact of sealed or partially-sealed fractures on permeability anisotropy in the Triassic Buntsandstein sandstone (1000-1400 m depth). We then propose a time scale for sealing through mineral precipitation.

Materials and methods

EPS1 was continuously cored from 930m onwards and the granitic basement was reached at 1417m.We targeted borehole core that best represented the variability preserved of fractures within the Buntsandstein unit for our study (Figure 1). The fractures are for the most part sub-vertical, have a thickness of 1-3mm, and contain various precipitated minerals. Some rare fractures can be up to around 1cm thick.Forty cylindrical core samples (40 mm in length and 20 mm in diameter) were prepared from the chosen borehole samples such that they contained healed or partially-healed fractures either parallel or perpendicular to their axis. We also prepared samples of the intact host rock, containing no fractures.These samples were then subject to gas porosityand gas permeability measurements. Permeability measurements were made using the steady state method, under a confining pressure of 1MPa. Thin sections were made for Scanning Electron Microscopy (SEM) to characterise the nature of the fractures and the precipitated minerals. In addition, X-Ray Diffraction (XRD)techniques were used to identify the bulk rock geochemistry.

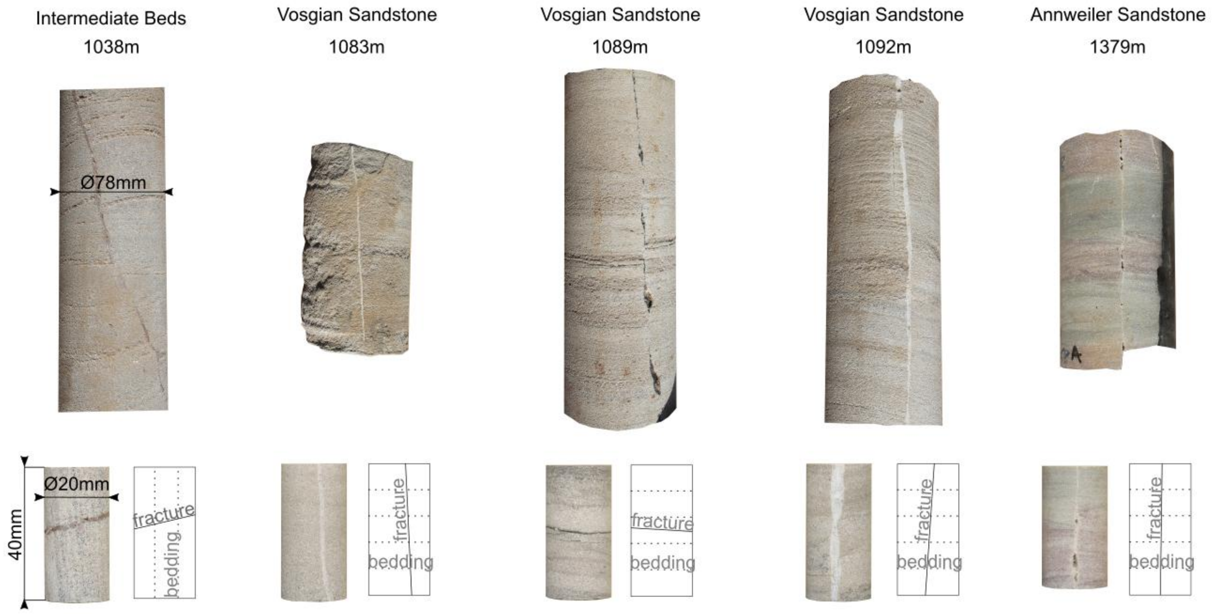

Figure 1. Examples of core (top) and the extracted plug samples (bottom) for each considered depth. Fractures are sub vertical and have a thickness in the millimetre scale.

Results

Permeability measurements of the Buntsandstein host rock yielded values ranging from 10^{-15} to 10^{-17} m^2 (Figure 3). For the 1038m deep (Figure 3a) samples, both the permeability and the porosity vary little; the fractures are no longer the conduits they may have once been and now their permeability is as low as the surrounding rock. At 1083m depth (Figure 3b) the rock is more anisotropic, we see that permeability is higher along the bedding but lower across fractures. The samples from 1089m depth (Figure 3c) have a more variable behaviour, where fracture permeability seems to depend on the extent of sealing. Finally, at 1092m depth (Figure 3d), the large barite fracture has a low permeability, though the surrounding rock is even less permeable. The samples from 1379m depth were too impermeable to be measured using our experimental setup.

Microscopic analysis suggests that prevalent pore-filling clays can explain the generally low permeability of the sandstone host rock. XRD results show that only clay is present in the pores, precipitated hydrothermal minerals were found onlyin fractures.

Discussion

The permeability of the Buntsandstein is on the whole very low. This is an important factor to consider when modelling fluid flow through the reservoir as the low permeability of these sediments can inhibit convection currents. It is likely that these fractures once represented effective conduits for flow but, as minerals were precipitated from the circulating hydrothermal fluids, the fractures healed and switched from providing conduits for flow to presenting barriers to flow. As a result, permeability anisotropy within these units could have changed over time. The variability in fracture sealing would suggest that fluid does not flow in large planar faults, but rather through more linear but tortuous pathways. Indeed, regional tectonics may be a constant cause of slip along fractures, keeping pathways open.

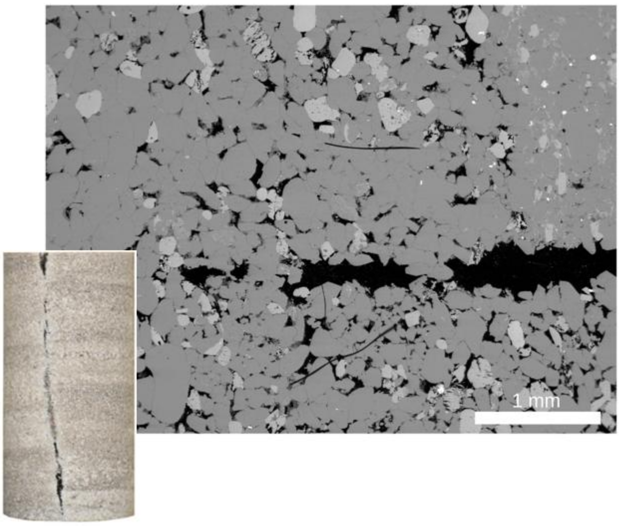

Figure 2. Left: A 40mm length and 20mm diameter sample from 1089 m depth. The bedding is in the radial direction and the fracture is in the axial direction. Right: SEM micrograph of a thin section of rock from the same depth containing a partially-sealed fracture. Darker areas are of lower density,and lighter colours are of higher densities.

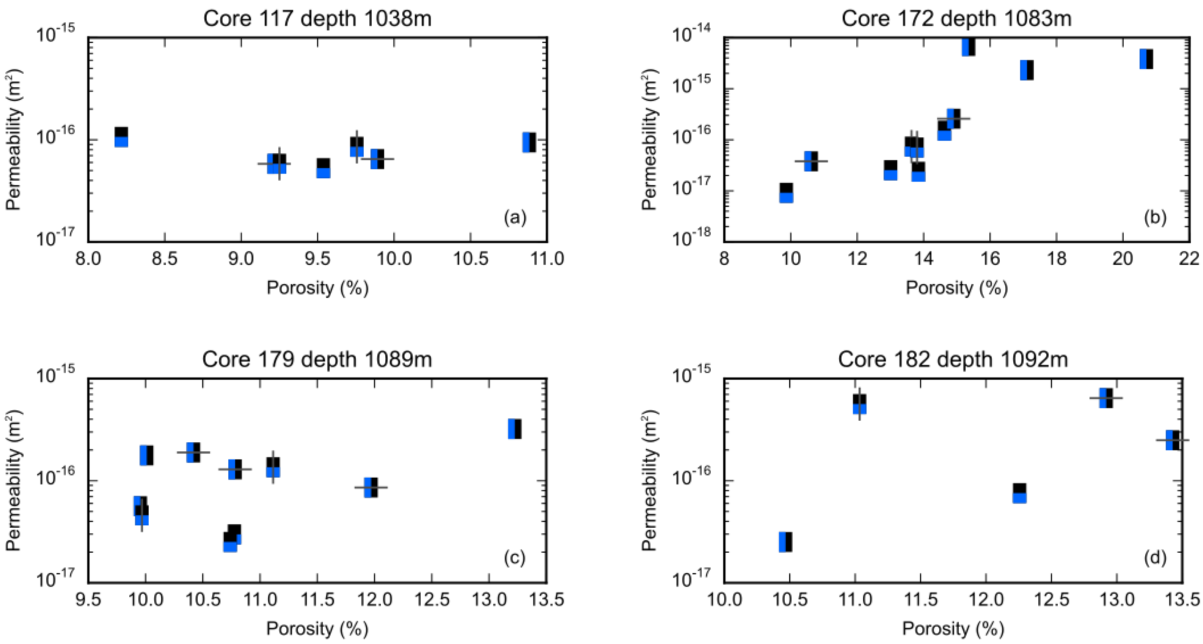

Figure 3. Permeability vs. porosity for samples from 4 depths. Vertical grey lines are fractures parallel to the sample axis and flow direction, horizontal lines are perpendicular. The direction of bedding in the sample is given in the same way, two vertical stripes for bedding parallel to flow and two horizontal layers for bedding perpendicular to flow.

To quantify the timescale over which fractures could heal, we used a model that utilises the brine composition data from the nearby well GPK1 at 1845m and 137 °C. From this we inferred the saturation index and precipitation rate constant of barite. This is the mineral present in the large, 3mm thick fracture in our 1092m depth samples and is a commonly found at geothermal sites. Assuming a 2nd order rate law and a spherical crystal geometry, we calculated the radial crystal growth rate of barite under these conditions. With a thin section of the sealed fracture we used polarised light to map out the crystal boundaries where their orientation changed. This gave an average crystal radius of 0.5mm and at 137°C the model predicts this would take 1 month to form (Figure 4).

We also calculated the growth rate at temperatures varying from 50°C to 250 °C (Figure 4).We see that if the temperature decreases then the precipitation rate increases dramatically, by up to two orders of magnitude between 20°C and 200°C. This explains the barite scaling we see at the surface installation where the circulating brine cools from around 160°C to 60°C. Barite is not only a mechanical hindrance, it also contains radioactive minerals which require an appropriate disposal.

The brine composition varies little with depth and mineral precipitation could alsobe a potential problem in the reservoir, around the injection wellbore, where intensive or long term production may cause significant cooling. In this case, the sealing of fractures around the well would affect injection rates and redirect fluid along other pathways. A stimulation strategy could take this in to account by studying well temperatures and deciding when hydraulic or chemical stimulation may be beneficial. It could also be worth using precipitation inhibitors to limit precipitation and fracture sealing.

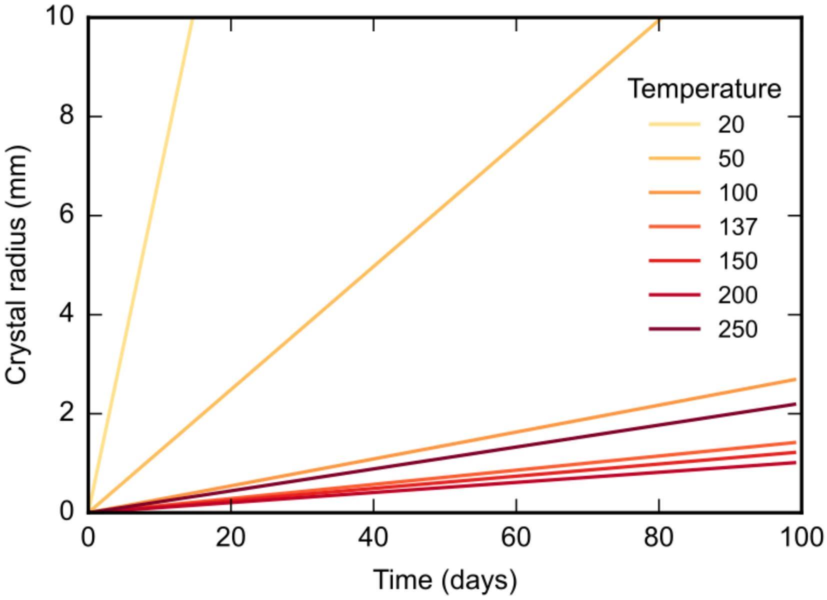

Figure 4. Barite crystal radius as a function of time at various temperatures.For temperatures of less than 200°C, the precipitation rate increases as temperature decreases.

Conclusion

The permeability of the Buntsandstein host rock was found to be very low due to the presence of pore-filling clay. As a result, fractures control regional fluid flow and their preferential distribution leads to permeability anisotropy. However, many of these are at least partially sealed by hydrothermal precipitates. Slip along fractures or chemical dissolution could open these fractures but they are at risk of sealing again where production causes a decrease in temperature. The high precipitation rates predicted by our model suggest that during production, if these problems are not mitigated, we may see efficient fracture sealing around the borehole, decreasing injectivity and ultimately production.