Barite precipitation: consequences on fracture permeability and injectivity at the geothermal sites of the Upper Rhine Graben

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ABSTRACT

In geothermal reservoirs, fluid circulation is greatly dependent on the geometry, density, and hydraulic properties of fractures. Here we present a combined experimental and modelling study that aims to provide insights into the impact of mineral precipitation on fracture permeability anisotropy in the Triassic Buntsandstein sandstone (1000-1400 m depth) at the Soultz-sous-Forêts geothermal site in Alsace, France. For our study, we targeted borehole samples that best represented the variability of fractures within the Buntsandstein. 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. These samples were then subject to porosity and permeability measurements, and thin sections were made for Scanning Electron Microscopy (SEM) to characterise the nature of the fractures and the precipitated minerals. SEM analysis suggests that prevalent pore-filling clays can explain the low permeability of the sandstone host rock. We found that fractures may present a conduit for or a barrier to flow, depending on the nature of the filling and the extent of sealing. We then modelled the crystal growth rate of barite with temperature to estimate a time scale for fracture sealing. (This extended abstract summarises the research reported in Griffiths et al., 2016).

1. INTRODUCTION

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. Core analysis and borehole wall imagery collected from reconnaissance well EPS1, drilled to a depth of 2230 m, revealed an extensive fracture network throughout the granite and overlying sediments, including both open fractures and fractures filled through mineral precipitation (primarily quartz, illite, chlorite, calcite, dolomite, barite, pyrite, and galena) (Genter and Traineau, 1996).

Figure 1: Photo of fractured Buntsandstein core from exploration well EPS1 at 1374 m depth. The rock contains a large fracture of roughly 1 cm in width, with precipitated barite crystals. Taken from Griffiths et al. (2016).

The Triassic Buntsandstein sandstone (1000-1400 m depth) is important for the regional fluid flow and temperature distribution. In this study we aim to quantify the effect of fracture sealing on permeability and permeability anisotropy in the Buntsandstein through laboratory porosity and permeability measurements on core samples. We then focus specifically on the precipitation of barite, which is abundant in fractures in the core samples, and we model the crystal growth rate with temperature, providing a time scale for sealing. Finally, we discuss the geothermal implications for permeability anisotropy and its time dependency due to mineral precipitation.

2. CORE DESCRIPTION AND MICROSRTUCTURE

2.1 Core samples

Figure 2: Photos of Buntsandstein core from exploration well EPS1 recovered from 1038, 1083, 1089, 1092 and 1379 m depth. The rock contains sub-vertical fractures up to several mm across. Taken from Griffiths et al. (2016).

For our study, we targeted borehole core from exploration well EPS1 (Figure 2) that best represents the variability of preserved fractures within the Buntsandstein. Core was selected from sections where the fracture density is noticeably greater, in the Upper Buntsandstein (1038 m depth), the Middle Buntsandstein (1083 m, 1089 m, and 1092 m depth), and the Lower Buntsandstein (1379 m depth). Heterogeneity in grain size and cementation is macroscopically visible between the selected samples. These core samples include sub-vertical fractures containing mineral precipitates. The fracture width ranges from 0.5 mm to 2 mm. These are representative of the preserved fractures in the EPS1 core (Vernoux et al., 1995) however, some larger fractures are also present (Figure 1). Slip along fractures can be observed, particularly in the case of the 1038 m, 1089 m, and 1379 m core samples where there is 5 – 10 mm of misalignment in bedding (Figure 2).

Forty cylindrical samples (nominally 40 mm in length and 20 mm in diameter) were prepared from the borehole core such that they contained sealed or partially-sealed fractures either parallel or perpendicular to their axis. These samples were cored either parallel or perpendicular to bedding (the orientations. We also prepared samples of the intact host rock, containing no fractures. Examples of the prepared samples are shown in Figure 5. These samples were then subject to gas porosity and gas permeability measurements. The connected porosity was calculated from the sample bulk volume measured using callipers and the rock matrix volume measured using a helium pycnometer (Micromeritics AccuPyc II 1340). Permeability measurements were made on jacketed samples using the steady state method, under a confining pressure of 1 MPa. Volumetric flow was measured using a gas flow meter for several pressure gradients across the sample. Two flow meters were used, one for high flow rates (i.e. high permeability samples) and one for low flow rates (i.e. low permeability samples). Darcy's law was used to calculate the permeability (applying the Klinkenberg or Forchheimer correction where necessary). The permeability range measurable with this setup is 10^{-18} – 10^{-11} m^2 (for more details see Farquharson et al., 2016; Heap and Kennedy, 2016).

2.1 Microstructure

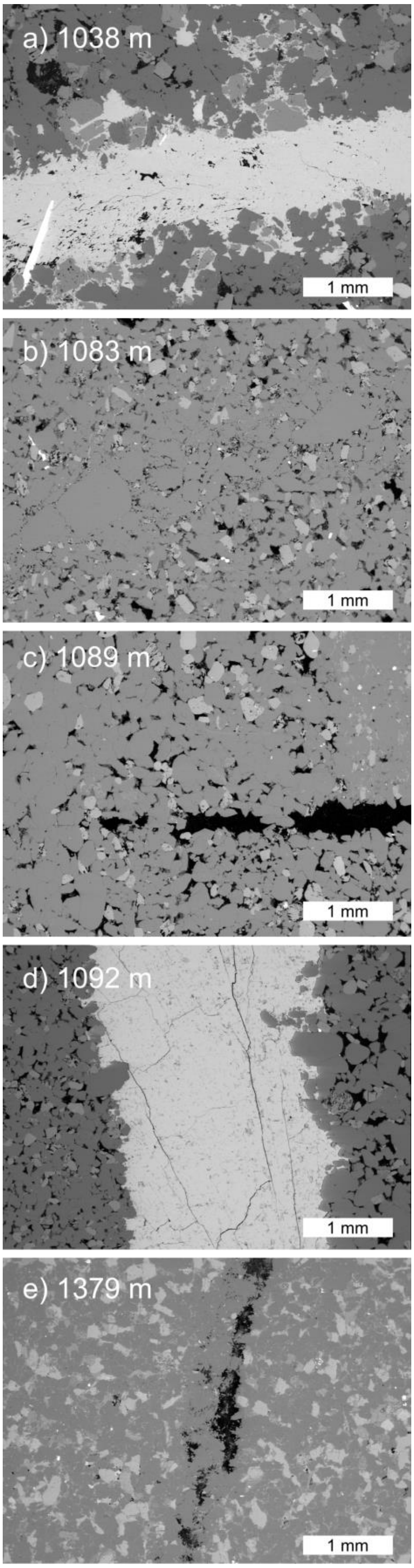

Figure 3: SEM micrographs of thin sections of rock containing a partially-sealed fractures. (a) and (d) show thick fractures sealed by barite precipitation. At the bottom left of (a), is an elongated siderite crystal. The fractures in (b), (c) and (e) contain quartz and K-feldspar. Both (c) and (e) show only partial sealing. Taken from Griffiths et al. (2016).

3. RESULTS

Connected porosity measurements of the intact Buntsandstein sandstone give values ranging from 2.9 % to 20.7 %, reflecting the high variability we see at the core scale. Permeability measurements of the Buntsandstein host rock yielded values ranging from 9.2 x 10-18 to 6.9 x 10-15 m^2. The samples from 1379 m depth were too impermeable to be measured using our experimental setup ($<10^{-18}$ m^2). Figure 4 is a synopsis plot containing all of measured permeability data against porosity, including samples cored both parallel and perpendicular to fractures.

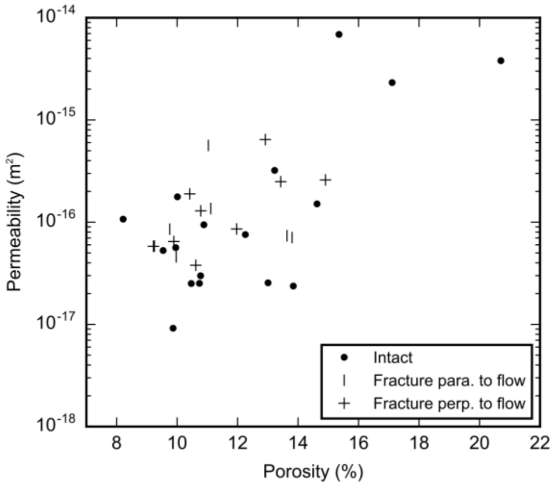

Figure 4: Resume plot of permeability against porosity for samples from 1038 m, 1083 m, 1089 m, and 1092 m depth. Samples are either intact, or contain fractures perpendicular or parallel to the direction of fluid flow. Taken from Griffiths et al. (2016).

Regarding the effect of bedding on fluid flow, Figure 5 shows the permeability against the porosity of intact samples from the core from 1083 m depth. We see that the permeability is orders of magnitude greater when flow is parallel to the bedding direction.

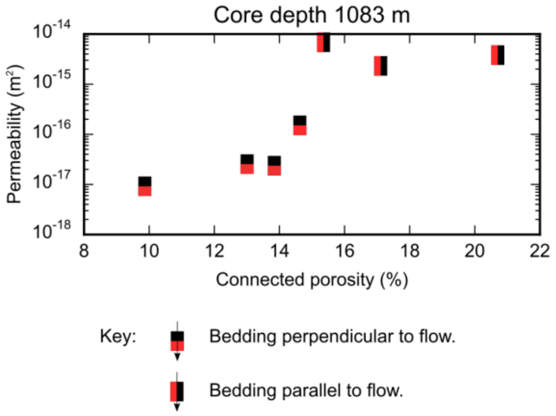

Figure 5: Influence of bedding on permeability for Buntsandstein core from 1083 m depth. Permeability is higher along the bedding. Adapted from Griffiths et al. (2016).

5. DISCUSSION

The permeability of the host Buntsandstein is generally lower than we might expect from sandstones of similar porosities (Bourbié and Zinszner, 1985; David et al., 1994; Zhu and Wong, 199); Vajdova et al., 2004; Baud et al., 2012). This is likely due to the presence of pore-filling clays (Figure 6). The permeability of the Buntsandstein is important for modelling fluid flow at Soultz-sous-Forêts. Indeed, assigning low permeability values (<10^{-14} m2) to the Triassic sediments has been shown to inhibit the formation of fluid convection cells (Magnenet et al., 2014). Although some layers may be permeable (>10^{-15}), the presence of low permeability layers would suggest that for large scale convection to occur within the Buntsandstein as a whole, open or partially sealed fractures must be available to facilitate fluid flow.

The presence of fractures appears to homogenise the permeability of the rock (Figure 4). On an individual basis however, the influence of fractures on permeability is more complex. Depending on the depth and the nature and extent of sealing, we see some permeability anisotropy in the fractures. In some cases, fractures remain conduits for flow, in others sealing is total and fractures are barriers to flow.

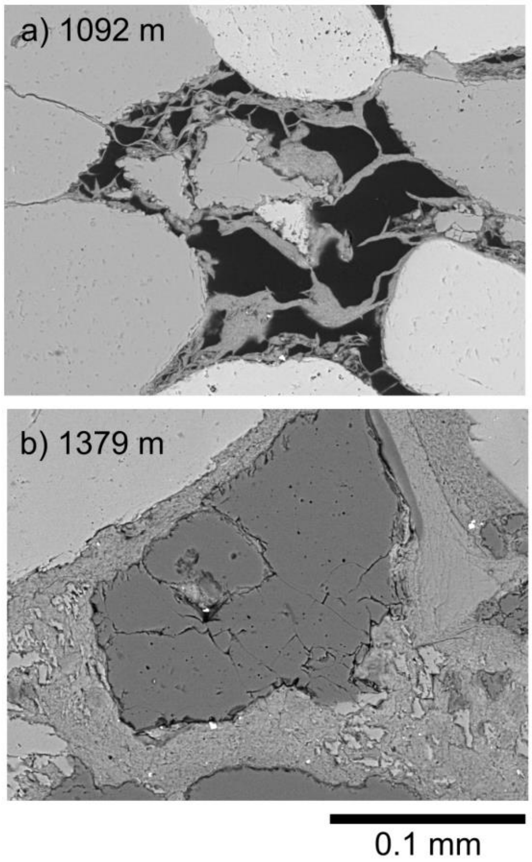

Figure 6: SEM micrographs of thin sections of Buntsandstein EPS1 core samples from (a) 1083 m (Karlstal Beds) and (b) 1379 m depth (Annweiler sandstone, known to have a high clay content). Pore-filling clays are visible in both images and at 1379 m depth they appear to occupy all available pore space. Taken from Griffiths et al. (2016).

Barite ($BaSO_4$) scaling is commonly observed in hydrocarbon reservoirs where highly concentrated brines are extracted from oil wells (Templeton, 1960). The same is true at the Soultz-sous-Forêts geothermal site, where it is abundant in the well core (Vernoux et al., 1995). Furthermore, barite is the most common precipitate in Soultz-sous-Forêts scaling and has been observed in pipes at the surface installations, where deposits can be several millimetres in thickness (Scheiber et al., 2013). Moreover, due to the extremely low solubility of barite, it requires mechanical removal (Christy and Putnis, 1993) which halts production and is both expensive and time consuming. Because of these risks, it is important to understand how quickly barite could precipitate in a geothermal context. Using a 2^{nd} order rate equation (Christy and Putnis, 1993) and the brine composition from a nearby well, GPK 1 (Sanjuan et al., 2010), we model the crystal growth rate of barite as a function of temperature (Figure 7). More details on this procedure are provided in Griffiths et al. (2016). We see that the precipitation rate of barite is much higher at lower temperatures and that under these conditions, fractures on the mm scale could seal in months to days.

The precipitation rate of barite increases dramatically with decreasing temperature (Figure 7). At the Soultz-sous-Forêts geothermal site, sulfate and sulphide scaling is particularly visible in the cold part of the surface installations where water is cooled from 160 °C to 60 °C, but scaling can even appear in the injection well (Scheiber et al., 2013).

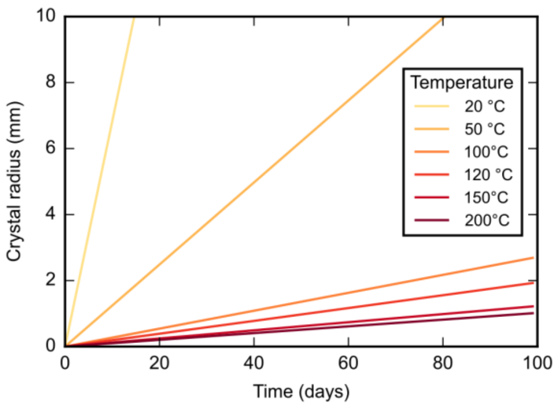

Figure 7: The modelled barite crystal radius against time for temperatures relevant to geothermal production. The crystal growth rate is lowest at temperatures of around 200°C, it then increases dramatically with decreasing temperature. Adapted from Griffiths et al. (2016).

We note that this simple model does not take into account the spatial variability of the precipitation rate due to the channeling of flow (Méheust and Schmittbuhl, 2001). Despite of these short sealing time scales, open and partially sealed fractures are still observed in the Buntsandstein, this could be explained by slip along fractures, keeping permeable pathways open.

Since fractures influence fluid flow in the reservoir, and its hydraulic connection to the injection well, mineral precipitation can have a large impact on geothermal production. The precipitation rate is a function of the temperature and composition of the injected fluids, both of which could potentially be controlled. The addition of chemical precipitation inhibitors to the injection fluid is also an efficient, but expensive, solution (e.g. Scheiber et al., 2013).

4. CONCLUSIONS

Generally speaking, open fractures are thought to affect the permeability and permeability anisotropy of geothermal reservoirs. In particular, the Triassic Buntsandstein sandstone (1–1.4 km depth), an important unit for regional fluid flow at Soultz-sous-Forêts, exhibits a dense fracture network. Microstructural observations of selected Buntsandstein core samples show how these fractures are variably sealed by precipitated minerals and therefore their influence on fluid flow is less predictable. We quantified, through porosity and permeability measurements, the hydraulic properties of the Buntsandstein. As a result of pore-filling clays, the values of permeability of the host rock are low. We found that the presence of low permeability sealed fractures can homogenise the permeability anisotropy (for example due to bedding), although we highlight that at the reservoir scale, fluids may find new vertical pathways through remaining open or partially-sealed fractures. These results show the importance of mineral precipitation at a geothermal site, as well injectivity and regional fluid flow depend on a reliable network of permeable fractures. Our precipitation model gives the crystal growth rate of barite as a function of temperature, showing it to increase as the geothermal fluid cools. This rate is potentially very high where geothermal fluids are cooling and suggests that the permeability of a geothermal reservoir around the injection well could vary greatly over the course of production.

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