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Geothermal implications for fracture-filling hydrothermal precipitation

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ABSTRACT

In geothermal reservoirs, fluid circulation is greatly dependent on the geometry, density, and hydraulic properties of fractures. The Soultz-sous-Forêts geothermal site located in the Upper Rhine Graben in Alsace, France, consists of a granitic basement overlain by a 1.4 km-thick sedimentary succession. Core analysis and borehole wall imagery collected from reconnaissance well EPS1, drilled vertically to a depth of 2230 m, revealed an extensive fracture network throughout the granite and overlying sediments, including both open fractures and fractures sealed through mineral precipitation (primarily quartz, illite, chlorite, calcite, dolomite, barite, pyrite and galena). Here we present a combined experimental and modelling study that aims to provide insights into the permeability anisotropy in the Triassic Buntsandstein sandstone (1–1.4 km depth) and the impact of mineral precipitation. We targeted borehole samples that best represented the variability of fractures within the Buntsandstein. Forty cylindrical samples (40 mm in length and 20 mm in diameter) were prepared from the chosen borehole samples such that they contained sealed or partially-sealed fractures either parallel or perpendicular to their axis. We also prepared samples of the intact host rock. 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. Permeability measurements of the Buntsandstein host rock yielded values ranging from 10^{-15} m^2 to less than 10^{-18} m^2. SEM and X-ray powder diffraction analyses suggest that prevalent pore-filling illitic clays can explain the low permeability of the sandstone host rock. Additionally, we found that the permeability of fractures depends on the nature of the filling and the extent of sealing, with barite providing the most effective precipitate. Taking into account the geothermal fluid composition at Soultz-sous-Forêts, we employ a kinetic model for the barite crystal growth rate with temperature to provide an estimate for the time scale over which open fractures can seal through barite precipitation (from months to days depending on temperature). The rate increases dramatically as the temperature of the geothermal brine decreases, highlighting the risk of mineral precipitation at geothermal sites, where fluid temperature fluctuates due to circulation through the reservoir rock and fluid mixing around the injection well. An improved knowledge of the time dependency of fracture permeability will provide insights into the permeability anisotropy in the Buntsandstein and may have repercussions for the geothermal exploitation and for the ongoing fluid flow modelling of the Soultz-sous-Forêts geothermal reservoir.

1. Introduction

Fluid circulation in geothermal reservoirs is susceptible to the geometry and hydraulic properties of fractures (Grant and Bixley, 2011). The Soultz-sous-Forêts Enhanced Geothermal System (EGS) is located in the Upper Rhine Graben in Alsace, France, and consists of a granitic basement overlain by a 1.4 km-thick sedimentary suc-

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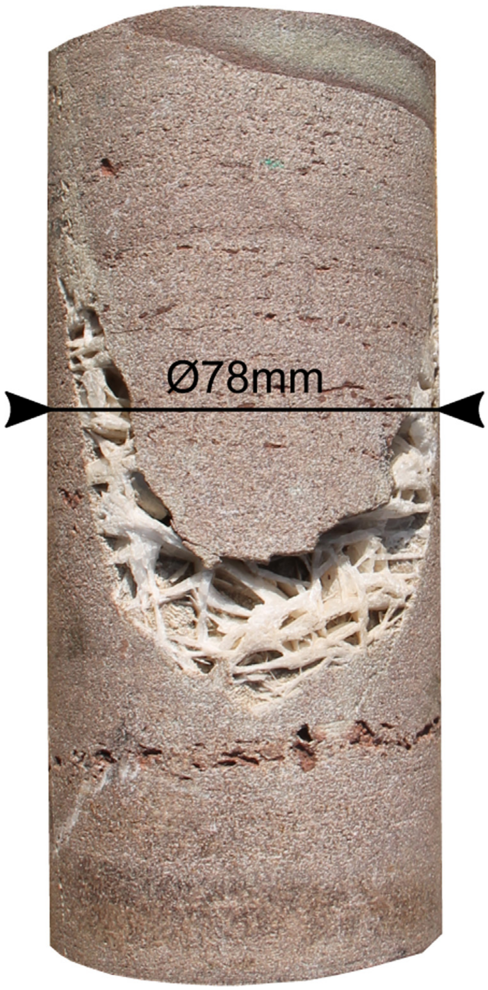

Fig. 1. Photo of a fractured Buntsandstein core sample from exploration well EPS1 at 1374 m depth. The rock contains a large fracture of roughly 1 cm in width, filled with precipitated barite crystals.

cession (Kappelmeyer and Gerard, 1989; Baria et al., 1999). This is a site of significant geothermal potential due to the high thermal gradient in the first 1 km of the sedimentary cover (~100 °C/ km) and the abundance of natural brines (Gérard et al., 2006; Genter et al., 2010). These brines have a high salinity, containing total dissolved solids of around 100 g/L and circulate over several kilometres, facilitating heat transfer (Sanjuan et al., 2010). Exploiting this natural heat source involves the use of deep wells and the fracture network in the granitic basement. The fracture network in the granite has been extensively studied (Dezayes et al., 2010; Genter and Traineau, 1996; Ledésert et al., 1993; Sausse et al., 2010; Surma and Géraud, 2003) as it is the target for two EGS heat exchangers at 3.5 and 5 km depth (Genter et al., 2010). In the Buntsandstein sandstone (1–1.4 km depth) and the granite below, the temperature gradient is lower (~30 °C/km and ~5 °C/km, respectively) than in the above sediments and has been linked to fluid convection (Pribnow and Clauser, 2000; Vidal et al., 2015). Numerical modelling of this hydrothermal convection at Soultz-sous-Forêts finds that the Buntsandstein, as well as the granite, plays an important role in controlling regional fluid flow (Guillou-Frottier et al., 2013; Magnenet et al., 2014).

Core analysis and borehole wall imagery collected from reconnaissance well EPS1 (Soultz-sous-Forêts), drilled vertically to a depth of 2230 m, reveal the geometry of an extensive fracture network throughout the granite and overlying sediments. This includes both open fractures and fractures filled through mineral

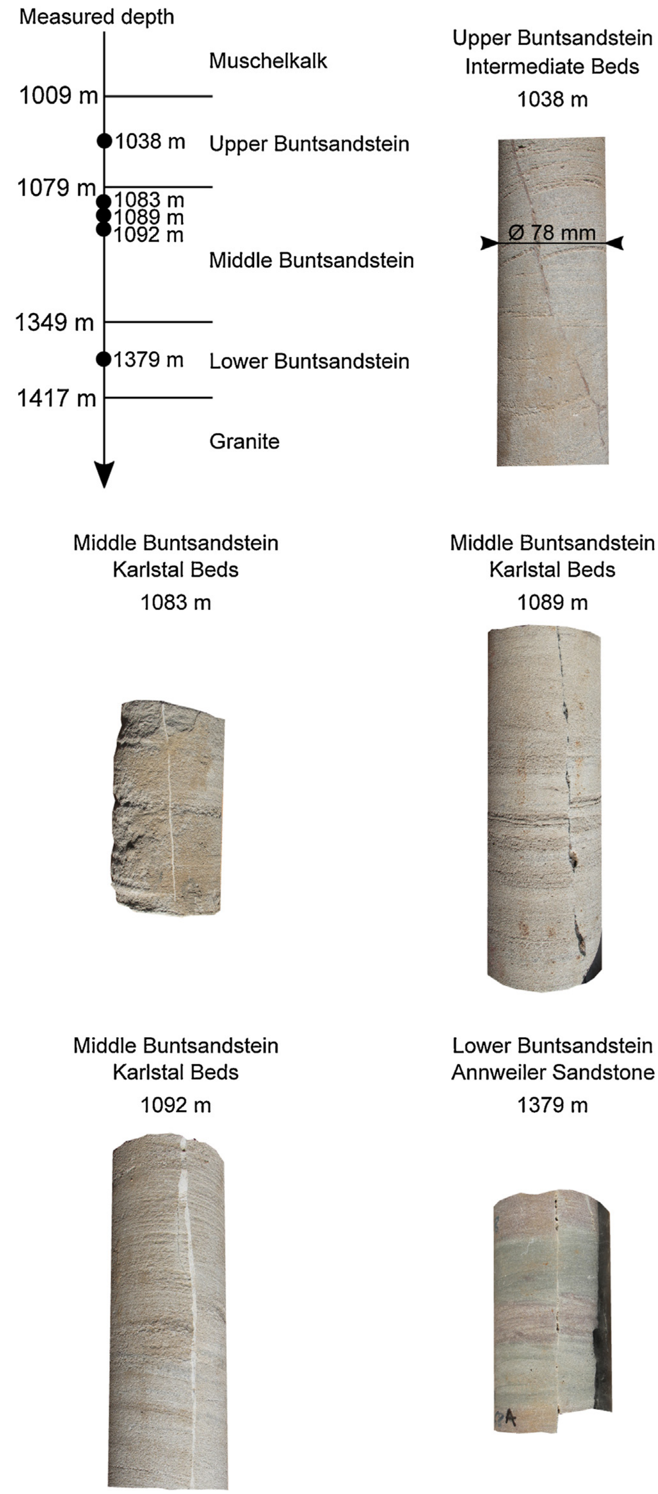

Fig. 2. Stratigraphy of and adjacent to the Buntsandstein, complete with the depths of the Formations (Muschelkalk, Upper, Middle, and Lower Buntsandstein, and the granite) and the depths of sampled cores from EPS1 (measured depths of 1038 m, 1083 m, 1089 m, 1092 m, and 1379 m). Photographs of the retrieved cores are also shown, which all contain sub-vertical sealed fractures with widths in the millimetre scale.

precipitation (primarily quartz, barite, calcite, and galena; Vernoux et al., 1995). EPS1 was continuously cored from 930 m to 2227 m measured depth and the granitic basement was reached at 1417 m (throughout this paper, all reported depths are measured depths). In the Buntsandstein (1000–1417 m depth in EPS1), core analysis