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Assessing the role of fractures on the permeability of the Permo-Triassic sandstones at the Soultz-sous-Forêts (France) geothermal site

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A B S T R A C T

Quantification of the systemic permeability of geothermal reservoirs is essential to the assessment of their economic feasibility. Here we investigate experimentally the role of fractures on the permeability of a 400 m-thick unit of Permo-Triassic sandstone from the EPS-1 exploration borehole in the Upper Rhine Graben near Soultz-sous-Forêts (France). The permeability of initially intact sandstone samples was measured before and after the introduction of a through-going tensile fracture. While the permeability of the fracture-free samples varied over five orders of magnitude between 1×10^{-19} and 1×10^{-14} m^2, the presence of through-going fractures increased sample permeability to between 8×10^{-14} and 4×10^{-12} m^2. Using the fracture aperture of open fractures provided by borehole televiewer data, we model the equivalent permeability down the borehole to be between 7×10^{-18} and 3×10^{-13} m^2, which is in agreement with values of hydraulic conductivity determined using borehole tests. Overall, these equivalent permeability values are not sufficiently high to sustain hydrothermal convection at Soultz-sous-Forêts, highlighting the need for continued anthropogenic stimulation.

1. Introduction

The economic viability of Enhanced Geothermal Systems (EGS) relies on the continuous movement of hydrothermal fluids within an active reservoir. For example, the development of economically feasible reservoirs in the Upper Rhine Graben (e.g. Soultz-sous-Forêts, France; Fig. 1) requires the presence of sustained kilometre-scale hydrothermal convection cells between the crystalline reservoir rock and the overlying sedimentary sequences. The convection of hot fluids in these systems can only be maintained above a threshold reservoir permeability (Pribnow and Schellschmidt, 2000; Lundgren et al., 2004; Graf and Therrien, 2009; Guillou-Frottier et al., 2013; Magnenet et al., 2014) and requires the presence of a network of open, reservoir-scale fractures (Genter et al., 1997; Haffen et al., 2013; Vidal et al., 2015).

In general, fluid circulation within the crust is reliant on large fracture networks (Walsh, 1981; Caine et al., 1996; Min et al., 2004). However, laboratory measurements have shown that the presence of shear fractures may act to both increase and decrease permeability in rock. While shear fractures in porous sandstones ($0.15 < \phi < 0.35$) may reduce rock permeability (Zhu and Wong, 1997), increases in permeability are observed with increasing inelastic strain in low porosity granite (Brace, 1978; Mitchell and Faulkner, 2008) and volcanic rock (Farquharson et al., 2016a). Similarly, laboratory studies have shown that extension fractures can increase the permeability of rock by several orders of magnitude (Morrow et al., 2001; Nara et al., 2011; Heap and Kennedy, 2016; Hofmann et al., 2016; Wang et al., 2016; Lamur et al., 2017; Pérez-Flores et al., 2017). The morphology of extension fractures plays a key role in governing fracture permeability, whereby increased fracture tortuosity (Heap and Kennedy, 2016) and roughness (Brown, 1987; Thompson and Brown, 1991; Zimmerman et al., 1992) act to decrease permeability. Further, the presence of fracture filling materials reduces permeability to varying degrees (Pérez-Flores et al., 2017). For instance, while fracture permeability is reduced by the presence of fault gouge, this decrease is moderated by particle size, where finer particle sizes act to more efficiently curtail fluid flow (Wang et al., 2016). Mineral precipitation also acts to effectively seal fractures and reduce permeability (Summers et al., 1978; Moore et al., 1994; Morrow et al., 2001), which can be especially disruptive to geothermal energy exploitation (Christy and Putnis, 1993; Scheiber et al., 2013).

The influence of open fracture space on rock permeability is often assessed using the cubic law (Witherspoon et al., 1980; Tsang, 1984; Pyrak-Nolte et al., 1987; Zimmerman and Bodvarsson, 1996), which models the permeability of a fracture as $k_f = \frac{d^2}{12}$, where d is the fracture aperture. The cubic law models laminar fluid flow between smooth parallel plates and is appropriately used when fracture apertures are

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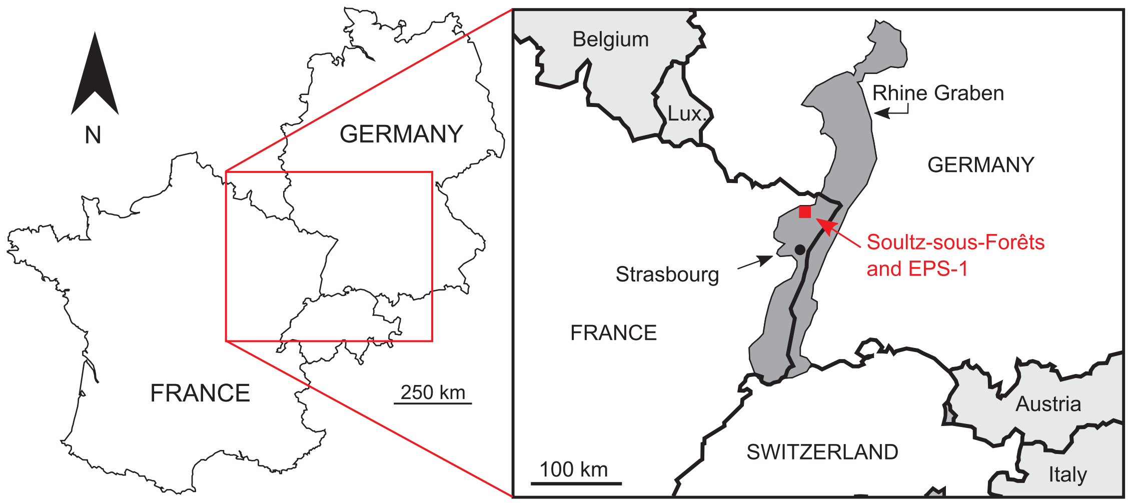

Fig. 1. Map of the Rhine Graben showing the location the EPS-1 exploratory borehole, approximately 5 km away from Soultz-sous-Forêts (France).

large or when fracture surfaces are smooth and straight. Under certain circumstances, however, rock fractures are not adequately described by ideal parallel plates (Brown, 1987; Pyrak-Nolte et al., 1987; Brown, 1989); as fracture tortuosity and fracture roughness increase, for instance, the fracture surfaces may be brought together and flow rates can deviate from those predicted using the cubic law (Tsang, 1984; Brown, 1987; Pyrak-Nolte et al., 1987; Zimmerman et al., 1992; Zimmerman and Bodvarsson, 1996). Indeed, when fractures are rough-walled, determining fracture aperture often becomes non-trivial (Witherspoon et al., 1980; Pyrak-Nolte et al., 1987; Brown, 1989; Zimmerman and Bodvarsson, 1996). Under these conditions, predicted permeability values may be significantly larger than those measured in the laboratory, though as much as 30% of the fracture surface may need to be in contact for laboratory measurements to deviate appreciably from models (Tsang, 1984).

Alternatively, the role of fractures on rock permeability can be investigated by adopting an effective medium approach (Vajdova et al., 2004; Baud et al., 2012; Heap and Kennedy, 2016; Hofmann et al., 2016; Farquharson et al., 2017a). This method assumes that the equivalent transmissivity of a unit of rock containing a planar structural feature oriented parallel to the direction of fluid flow can be described by:

$$Ak = A_i k_i + A_f k_f \tag{1}$$

where A is the cross-sectional area of the entire rock unit perpendicular to flow, k is the equivalent permeability of the rock unit, A_i is the cross-sectional area of the intact rock, k_i is the permeability of the intact rock, A_f is the cross-sectional area of the structural feature, and k_f is the permeability of the structural feature (Fig. 2A). Importantly, this effective medium approach considers the contribution of the proportions of both the structural feature and the intact rock to overall permeability. This method is especially convenient in the case of fractured rocks when the permeability of the intact and fractured rock can be measured in the laboratory since it avoids the necessity of characterizing fracture topography and is mathematically less sensitive to fracture aperture than the cubic law.

The Upper Rhine Graben is characterized by a crystalline (Paleozoic granite) basement (Genter and Traineau, 1996) overlain by Permo-Triassic sediments (Aichholzer et al., 2016). The geothermal potential within the Upper Rhine Graben is constrained to an extensive zone of geothermal convection between 1 and 3.5 km depth, where the geothermal gradient is 5 °C/km (Pribnow and Schellschmidt, 2000); the top of this convection zone is rooted in the Permo-Triassic sandstones and overlying Triassic Muschelkalk sediments (Vidal et al., 2015). Tertiary and Mesozoic sediments overlie the convective zone, acting as a regionally low-permeable layer that caps and insulates the hydrothermal system (Pribnow and Schellschmidt, 2000; Vidal et al., 2015). While the Paleozoic granite basement is currently being exploited as the reservoir at the Soultz-sous-Forêts (Kappelmeyer et al., 1991; Baria et al., 1999; Gérard et al., 2006) and Rittershoffen (France) (Baujard et al., 2017) EGS sites, the transition between the granite and overlying sediments is also of economic interest. Indeed, the geothermal potential of this transition zone has been demonstrated at Cronenbourg and Rittershoffen (France) and Landau, Insheim, and Bruchsal (Germany) (Housse, 1984; Baumgärtner and Lerch, 2013; Hettkamp et al., 2013; Villadangos, 2013).

Most geothermal-related research in the Rhine Graben has focused on the crystalline basement (Genter and Traineau, 1996; Genter et al., 1997; Sausse et al., 2006; Dezayes et al., 2010; Ledesert et al., 2010), while relatively few studies have looked at the role of permeability within the sedimentary cover (Haffen et al., 2013; Vidal et al., 2015; Griffiths et al., 2016; Heap et al., 2017). The matrix permeability of the Permo-Triassic sedimentary cover, including the Buntsandstein, varies over five orders of magnitude (between 10^{-19} and 10^{-13} m^2) (Griffiths et al., 2016; Heap et al., 2017). While these studies have shown that there is no appreciable permeability anisotropy in most of the Buntsandstein, some units are more permeable parallel to bedding − rather than perpendicular to bedding – by less than an order of magnitude. Critically, the permeability of the matrix of most of the Buntsandstein units is below the numerically modelled threshold permeability required to sustain kilometre-scale convection cells in the Soultz-sous-Forêts geothermal system (Graf and Therrien, 2009; Magnenet et al., 2014). Regional hydrothermal convection is sustained, instead, by a series of fracture zones that regionally increase the permeability of the sedimentary cover (Vidal et al., 2015). However, these fractures can be subject to rapid sealing due to secondary mineral precipitation (Griffiths et al., 2016), requiring periodic anthropogenic stimulation of the reservoir to reopen permeable pathways.

Assessing the role of reservoir-scale structural features on the hydraulic properties of reservoirs is challenging. Physical property measurements made in the laboratory are limited by sample size thus, while the physical properties of intact rock are easily characterized, such measurements preclude the effect of larger-scale structural features, such as fracture networks. Indeed, comparing permeability data from intact core samples (Griffiths et al., 2016; Heap et al., 2017), which represent the matrix permeability of the reservoir rock, with the hydraulic conductivity determined from large-scale borehole hydraulic tests demonstrates that the matrix permeability is often far lower than that of the reservoir as a whole (Stober and Bucher, 2015). In this study, we investigate experimentally - using the effective medium approach -