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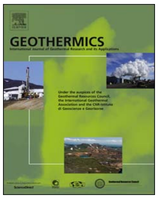

Overview of naturally permeable fractured reservoirs in the central and southern Upper Rhine Graben: Insights from geothermal wells

Jeanne Vidal[a,*], Albert Genter[b]

[a] *IPGS, University of Strasbourg, 1 Rue Blessig, 67084, Strasbourg Cedex, France*
[b] *ES-Géothermie, Bâtiment Belem, 5 Rue de Lisbonne, 67300, Schiltigheim, France*

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ABSTRACT

Since the 1980′s, more than 15 geothermal wells have been drilled in the Upper Rhine Graben (URG), representing more than 60 km of drill length. Although some early concepts were related to purely matrix-porosity reservoirs or Hot Dry Rock systems, most projects in the URG are currently exploiting the geothermal resources that are trapped in fracture networks at the base of the sedimentary cover and in the granitic basement. Lessons-learnt from the European EGS reference site at Soultz-sous-Forêts reveal highest natural permeability in the uppermost altered crystalline basement.

Here, we present a compilation of related information to examine a more general validity of this hypothesis for the central URG. In this respect, 15 geothermal wells were analyzed concerning their lithologies, temperature distribution with depth, and their hydraulic yields. Among others, permeable fractures in Triassic sediments were observed among others during drilling operations at Soultz-sous-Forêts, Rittershoffen, Cronenbourg (France), Landau, Insheim, Bruchsal and Brühl (Germany). The geothermal wells at Soultz-sous-Forêts, Rittershoffen (France), Landau and Insheim (Germany) also intersect well-connected fracture networks in the uppermost altered granitic basement. Permeable fractures are intersected to a depth of 5 km at Soultz-sous-Forêts (France) and Basel (Switzerland).

The compilation of geologic, hydraulic and thermal data of 15 geothermal wells shows permeability variation among the lithologies with the maximum observed at the top of the hydrothermally altered granite. This higher permeability is likely due to the intense fracture density in the fault core of the fracture zone and the large porous and altered damage zone which allow connection with the reservoir.

1. Introduction

The Upper Rhine Graben (URG) is a part of the European Cenozoic Rift System. This graben is characterized by a series of thermal anomalies that are widely interpreted as the signature of large-scale natural advection and convection on multi-scale fracture-controlled systems. These systems are associated with the nearly vertical faults that cross-cut both the deep-seated Triassic sediments and the Paleozoic crystalline basement rocks (Baillieux et al., 2013; Pribnow and Schellschmidt, 2000; Schellschmidt and Clauser, 1996). In both cases, fracture permeability exceeds matrix permeability. The overlying Tertiary sedimentary formations exhibit exceptionally high temperature gradients up to 100 °C/km and host hydrocarbons (Sittler, 1985). Over the past 35 years, geothermal projects have been developed in France, Germany and Switzerland to exploit deep geothermal energy.

Starting in Los Alamos (USA) and Cornwall (UK) in the 1970s, the exploitation of granitic systems was initially developed based on the Hot Dry Rock (HDR) concept. The HDR concept was initiated to exploit the vast energy resources that reside as heat in the low-permeability rocks underlying most continental regions at depths accessible by wells (Schulte et al., 2010). The Soultz-sous-Forêts pilot project includes five deep wells intersecting the Triassic sediments and reaching the deep crystalline basement. Initially, HDR technology was used to artificially create a heat exchanger in the deep crystalline rocks. However, all wells exhibit at least one permeable natural fracture zone. The natural permeability of these fracture zones is often weak and needs to be enhanced to reach economically viable hydraulic yields. Thus, these reservoirs are often associated with Enhanced Geothermal System (EGS) technology, which involves engineering existing fractures to improve their low initial permeability (Ledru and Guillou-Frottier, 2010). At Soultz, the top basement is characterized by intense hydrothermal alteration (Traineau et al., 1992), where the flowrate is higher even if the temperature of the geothermal fluid is lower. It is well known that the natural reactivation potential and the susceptibility of fractured

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[*] Corresponding author.
E-mail address: jeanne.vidal@es.fr (J. Vidal).

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reservoirs to hydraulic stimulation is influenced by the lithology (Meixner et al., 2014) and in the particular case of the granitic basement, the degree, of hydrothermal alteration (Evans et al., 2005; Meller and Kohl, 2014). Recent geothermal projects are directly based on lessons learned from Soultz projects, where the initial natural permeability is highest in the fracture networks at sediment-basement interfaces (Schill et al., 2017). They are described as hydrothermal systems, and their economic exploitation does not require stimulation treatments.

In this paper, we investigate to what extent the observations at Soultz are systematic and representative of the central URG sediment-basement interface. To achieve this, 15 wells are compared with regard to their lithological differences and respective temperature and hydraulic indicators. These data are discussed in relation to observed fracture zones. Because hydraulic parameters are of critical economic relevance and are typically not publically available, temperature is used to infer heat transfer processes and, thus, hydraulic conditions in most cases. Following a presentation of fractured systems and hydrothermal circulation concepts in the URG, deep geothermal projects of the central and southern URG are discussed. The geothermal project of Soultz-sous-Forêts serves as a reference.

2. Structural evolution of the URG

The Upper Rhine Graben (URG) forms the central, most conspicuous segment of the ECRIS (Illies, 1965), which extends over a distance of more than 1000 km from the North Sea to the Mediterranean (Fig. 1). The NNE-trending URG, which is limited by the Rhenish Massif to the north and the Jura Mountains to the south, has a length of some 300 km and a width of 30–40 km. This geological setting will focus on the structural inheritance of the crystalline basement and the evolution of fractured system from Variscan to late Alpine.

The Variscan crystalline basement of the URG is characterized by three major tectonic terranes, oriented NE to NNE, from north to south, the Rhenohercynian, the Saxothuringian and the Moldanubian that present major lithological differences (Edel and Schulmann, 2009; Edel and Weber, 1995; Ziegler, 1990). They are intruded by carboniferous granitoid (340 Ma (Visean) and 270 Ma (Permian)) that exhibit a large petrological and geochemical diversity of crystalline rocks, which are related to a variety of active deep magmatic sources and different petrogenetic mechanisms (Altherr et al., 2000, 1999; Edel and Schulmann, 2009; Lagarde et al., 1992). These granitoids are emplaced following a NE to NNE direction according to main weakness zones such as collisional or shear zones. These inherited Hercynian NE to NNE-striking crustal weakness were reactivated to the URG formation under compressional stresses during Alpine and Pyrenean collisions (Dèzes et al., 2004; Edel et al., 2007; Illies, 1972, 1965; Schumacher, 2002; Villemin and Bergerat, 1987). Mesozoic platform sediments of Triassic (Buntsandstein, Muschelkalk and Keuper) and Jurassic (Lias and Dogger) times that results from eroded Variscan belt are also affected by structural evolution during Cenozoic rifting. (Villemin and Bergerat, 1987) and (Schumacher, 2002; Villemin and Bergerat, 1987) proposed a Cenozoic rifting of the URG divided into four brittle deformation phases, which were accompanied by different stress regimes from the late Eocene rifting to the late Miocene. The first phase (middle to late Eocene) was characterized by an N–S compressive regime. During the second phase (late Eocene to late Oligocene), major E–W extension resulted in the greatest rifting and the development of thick sedimentary sequences in the URG (Doebl, 1967). These events included two marine transgressions, which induced the deposition of the carbon-rich Pechelbronn layers and salt layers in the southern area of the graben, among others. During the early Miocene, the stress regime changed to an NE–SW-oriented compressive phase. This episode was characterized by the uplift of the upper mantle and crust, as suggested by the up-doming Moho and the beginning of volcanism at the Vogelsberg and Kaiserstuhl volcanos (Fuchs et al., 1987). The prevailing stress regime in the URG from the late Miocene to the present has been a compressional regime with an NW–SE orientation, as observed over much of central Europe, which resulted in a left-lateral transcurrent motion (Bergerat, 1985; Illies and Greiner, 1979).

3. Thermal settings and fractured system

In the URG, the underground temperature distribution is spatially heterogeneous with a series of local anomalies with temperatures above 140 °C at 2 km Measured Depth (MD). Most of these values are concentrated on the western side of the URG, where the direction of the border fault rotates from N20°E to N45°E (Baillieux et al., 2014, 2013; Dezayes et al., 2015; Schellschmidt and Clauser, 1996). High resolution temperature data from wells reveal a spatial link between high temperature and local faults, such as the Soultz and Kutzenhausen faults, as well as the Ω-fault at Landau (Fig. 1) (Bächler et al., 2003; Baillieux et al., 2013; Benderitter et al., 1995; Pribnow and Clauser, 2000; Pribnow and Schellschmidt, 2000). Thus, these geothermal anomalies at the local scale are attributed to buoyancy-induced hydrothermal circulation in fractures within the crystalline basement and sandstones. For example, Fig. 2 shows the disturbance of isotherms resulting from geostatistical modelling (GeORG Team, 2013). The so-called 'Soultz geothermal anomaly' is one of the most important temperature anomalies and has been the subject of numerous studies. Hydrothermal convection may explain 75–85% of this anomaly (Baillieux et al., 2013), and the up-flow of thermal water occurs mainly along westward dipping normal faults (Baillieux et al., 2014). The radiogenic heat production due to the crystalline composition of the basement may explain the remaining 15–25% (Baillieux et al., 2013). The highest radiogenic productions are associated with hydrothermally altered zones. In the deep geothermal well GPK-1, radiogenic production determined from core samples ranges between 5.5–6.5 μW/m3 for depths between 1400 and 1550 m MD (Rummel et al., 1988). Continuous logging of the deep geothermal well GPK2 revealed values up to 7 μW/m3 between 3700 and 3800 m MD and at 5060 m MD in permeable zones (Grecksch et al., 2003; Pribnow, 2000).

All geothermal fluids collected in deep geothermal wells result from the mixing of primary marine brine (seawater evaporation at least up to the halite precipitation stage) and water of meteoric origins (Aquilina et al., 1997; Pauwels et al., 1993; Sanjuan et al., 2014, 2010). These fluids are of the Na-Cl type with high salinity values, approximately 100 g/L, and with pH values close to 5 (Sanjuan et al., 2016, 2014). Both fossil and present-day hydrothermal circulations in the fracture system have resulted in the strong dissolution of primary minerals, such as biotite and plagioclase, as observed in the granitic basement of Soultz, as well as the significant deposition of some altered minerals, such as clay minerals (smectite, illite, tosudite), calcite, secondary quartz and sulfides (Genter and Traineau, 1992). Circulation ages have been estimated from fracture filling dating at Soultz. Illites from fracture veins revealed ages from the Permian, Cretaceous, Miocene and earlier (Bartier et al., 2008; Schleicher et al., 2006). Hydrothermal circulations may have been linked to major volcanic events in the URG during the Permian (Lorenz and Nicholls, 1976), Cretaceous and Miocene (Illies, 1972). Mineralogical studies of assemblages in fracture fillings indicate a complex polyphase circulation system (Dubois et al., 2000; Smith et al., 1998).

4. History and structural setting of the geothermal wells

Table 1 and Figs. 3 and 4 show the geothermal wells used in this study, which are located in the central and southern URG, as well as their structural setting in chronologic order.

Triassic sediments were assessed in the early 80 s with the objective of exploiting the Mesozoic aquifers. In this context, the geothermal well GCR-1 was drilled in 1984 at Cronenbourg (Alsace, France) into the sandstones of the Buntsandstein (Lower Triassic age) (Housse, 1984).