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Identification of Fluid Circulations at the Borehole Scale from Temperature Logs: Insights from Deep Geothermal Wells in the Upper Rhine Graben

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ABSTRACT

In the Upper Rhine Graben (URG), geothermal projects since 40 years targeted hot geothermal anomalies with temperatures above 140°C at 2-km, observed at the regional scale. They are mainly concentrated on the western side of the URG, around N-S striking local faults that channelize hot geothermal resource corresponding to native brine. The so-called Soultz and Rittershoffen anomalies located in France were widely investigated from the regional to the more local scale. At the borehole scale, the vertical circulations of the brine in the fracture and fault zones surrounded by a damage zone are also evidenced in temperature (T) logs. T logs are affected by discrete T anomalies in the convective regime section that spatially match with several meters-thick fracture zones (FZ) observed on core or cutting samples, geophysical logs and image logs. At Soultz, these T anomalies were all negative at thermal equilibrium and interpreted as the remnant cooling of porous damage zones after mud invasions during drilling operations and water injection during stimulation operations. In this study, the dataset of T logs in production and at thermal equilibrium in the wells of Soultz and Rittershoffen evidences a new interpretation of these T anomalies. At equilibrium, a negative anomaly indicates that geothermal brine circulating through the FZ is colder than the surrounding rock formation. During production, this T anomaly can be positive that indicates inflow of water hotter than the mix of water circulating below. Thus, the polarity of the T anomaly can change over the time depending of the state of thermal equilibrium. Negative anomalies are more often observed because fractures are direct paths for cold mud or water during drilling and hydraulic operations and are thus cooled faster than the rest of the rock formation. Because temperature flux and geothermal fluids are intimately linked, the T logs are a useful, reliable and very sensitive tool to localize and characterize the inflow of geothermal water through FZs at the borehole scale. The recent T logs acquired in injection in the newly drilled well GIL-1 at Illkirch geothermal site (Strasbourg, France) allow to localize the permeable zones in the granitic reservoir. T logs of the URG evidenced that the most permeable reservoirs were intersected at the first hundred meters of the granitic basement; 700m at Soultz, 200-400m at Rittershoffen, more than 400m at Illkirch.

1. INTRODUCTION

During the past decade, the need for meaningful tool for localization and characterization of natural fluid circulations at the borehole scale became crucial for geothermal development and fluid extraction. Nowadays, in the Upper Rhine Graben (URG), a new drilling approach was developed, which designed deviated well trajectories crosscutting highly dipped fault zone in the altered granitic basement in order to maximize the connection between the well and the natural reservoir. Once the well drilled, the characterization of the hydrothermal circulations at the borehole scale is a key challenge for the success of the project. Hydrothermal circulations are channelized by the fracture network intersected by the well (Schellschmidt and Clauser, 1996). Experience shows that the characterization of these circulations by flow logs (obtained with a spinner tool) is difficult because flow logs are hard to obtain and interpret in the fractured reservoirs. In contrast, temperature (T) logs are cheap and easily acquired and interpreted. T anomalies are interpreted as the thermal expressions of permeable fracture zones (FZs) in several deep wells in geothermal systems worldwide (Barton et al., 1995; Bradford et al., 2013; Dezayes et al., 2010; Evans et al., 2005; Mas et al., 2006).

At Soultz-sous-Forêts (Alsace, France), negative T anomalies are interpreted as the remnant cooling of porous damage zones after mud invasions during drilling operations and water injection during stimulation operations (Genter et al., 2010). However, observations from T logs evidenced that the polarity of the T anomalies could vary over the time or that hydraulic operations in the well could disturb these anomalies without concrete interpretations. In this paper, the dataset of the T logs acquired from wells at equilibrium and during production, combined with flow logs when they are available, offers a unique chance to further interpret T anomalies at the borehole scale. The reinterpretation of T logs at equilibrium and during production in wells GPK-1 and GPK-2 at Soultz-sous-Forêts and GRT-1 and GRT -2 at Rittershoffen (Alsace, France) provides a new perspective to better understand brine circulation through FZs in the granitic basement. The goal is to propose an interpretation of the T anomalies in the fractured reservoir based on these anomalies and a conceptual model of fluid circulations through the FZs at the borehole scale.

2. GEOLOGICAL SETTINGS

The URG is a Cenozoic rift affected by several extensional and compressional tectonic phases which developed a multi-scale fracture network (Schumacher, 2002; Villemin and Bergerat, 1987). The resulting fault network acts as preferential pathways for fluids circulations that lead to hot geothermal anomalies concentrated around local normal faults (Baillieux et al., 2013; Benderitter and Elsass, 1995; Pribnow and Clauser, 2000; Pribnow and Schellschmidt, 2000). 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). Homogenization temperatures measured from fluid inclusions on secondary quartz and carbonate visible on fractured Soultz core samples showed a narrow temperature range which is consistent with the present-day in situ temperature field measured in the Soultz wells (Dubois et al., 2000). Quartz and ankerite are likely to precipitate at present suggesting that the geothermal fluid probably has a pulsated mode of circulation. Isotopic study done on similar fracture filling (quartz, carbonate) showed that only calcite minerals located in a permeable zone at 1813m in GPK1 well is in equilibrium with the present-day geothermal fluids (Fouillac and Genter, 1992). 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).

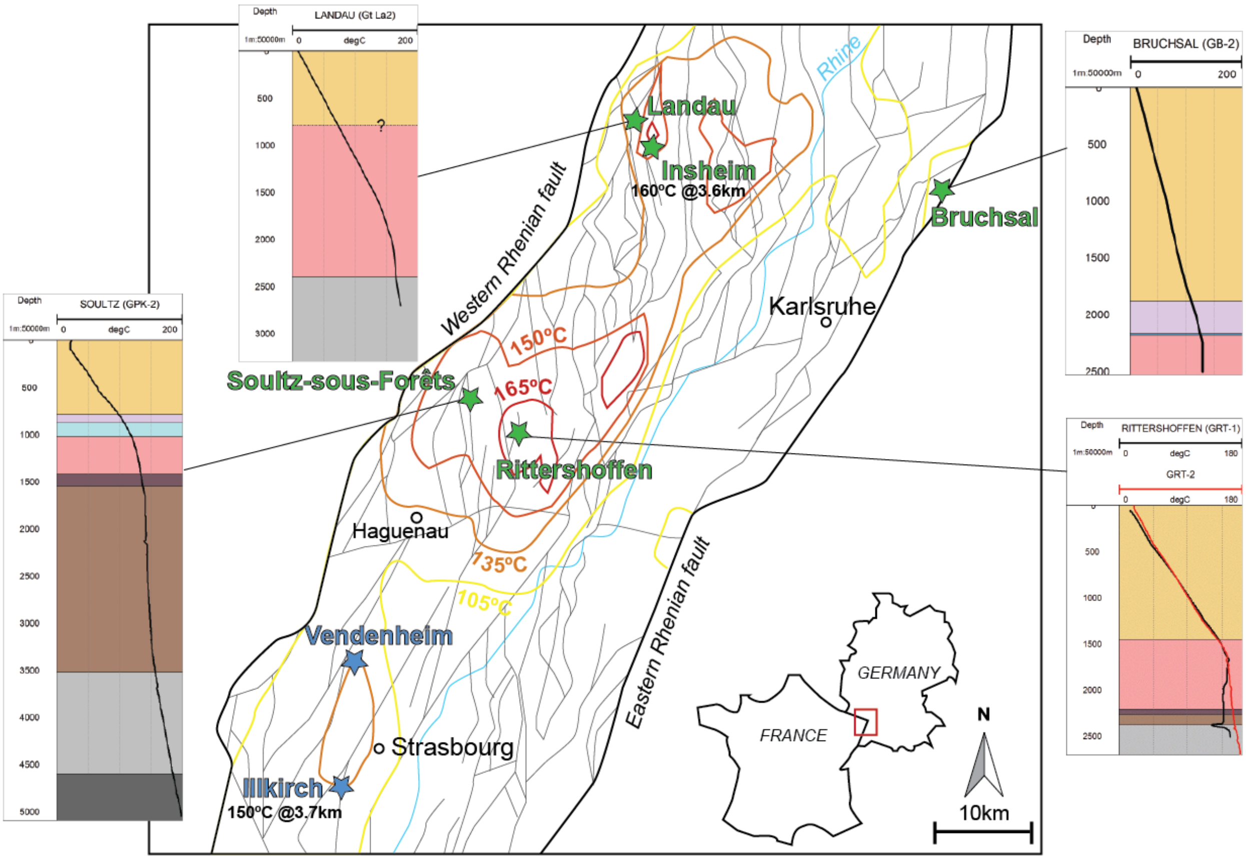

Figure 1 Structural map of the center of the Upper Rhine Graben with isotherms at 2 km depth from the geoportal GeORG (GeORG Team, 2017). The geothermal anomaly in the Strasbourg area is from the dataset of Baillieux et al. (2013). Geothermal power plants in operation are represented by green stars, and the geothermal projects under drilling operations are represented by blue stars. Temperature data are from **(Baujard et al., 2017; Baumgärtner and Lerch, 2013; Genter et al., 2010; Herzberger et al., 2010; Schindler et al., 2010)**. T logs at equilibrium in Soultz, Landau, Bruchsal and Rittershoffen. On geological log, yellow = Cenozoic and Jurassic sediments, light purple = Keuper sediments, blue = Muschelkalk sediments, pink = sandstones sediments, deep purple = reddish granite, brown = highly altered porphyritic granite, light grey = porphyritic granite, deep grey = two-mica granite.

The Fig. 2 shows the disturbance of isotherms at 2km depth Measured Depth (MD) from geostatistical modelling (GeORG Team, 2013). These geothermal anomalies are attributed to hydrothermal circulation of a high salinity brine (100g/L) in fractures within the crystalline basement and sandstones (Sanjuan et al., 2016). They occur mainly along N-S striking and westward dipping normal faults (Baillieux et al., 2014). Over more than 30 years, 18 deep geothermal wells have targeted these faults in Germany (Landau, Insheim, Bruchsal, and Brühl) and France (Soultz-sous-Forêts, Rittershoffen and, most recently, Illkirch and Vendenheim) (Baujard et al., 2017; Baumgärtner et al., 2005; Baumgärtner and Lerch, 2013; Hettkamp et al., 2007; Reinecker et al., 2019; Vidal and Genter, 2018). The bottomhole temperature reaches 200ºC at 5km depth at Soultz, 160ºC at 2.6km depth at Landau, 160ºC at 3.6km depth at Insheim, 177ºC at 3.2km depth at Rittershoffen, 135ºC at 2.5km depth at Bruchsal and more recently about 155ºC at 3.8km depth at Illkirch (Figure 1). Temperature (T) logs obtained from these wells confirm the presence of hydrothermal convection and assert the roles of faults and fracture zones (FZs) as preferential pathways for geothermal brine. The top of the granitic basement, which is highly fractured and affected by hydrothermal alteration, presents a low geothermal gradient associated with the vertical flow of brine (Genter et al., 2010; Pribnow and Schellschmidt, 2000). T logs show a gradient of 10ºC/km at Soultz, 20ºC/km at Landau, between 0 and 15ºC/km at Rittershoffen, and null at Bruchsal (Figure 1). The low geothermal gradient is not observed anymore above the Muschelkalk formations and the soft Cenozoic, Jurassic and Keuper sediments act as a caprock for the convective regime below (Vidal and Genter, 2018). Considering that the fracture system is highly dipping in both the basement and the deepest sedimentary formations (Buntsandstein, Muschelkalk), natural fluid circulations take place on a large vertical scale. Consequently, the low geothermal gradient is locally affected by T anomalies interpreted as the thermal signatures of the highly dipping permeable FZs intersected by the well (Dezayes et al., 2010; Evans et al., 2005; Genter et al., 2010; Vidal et al., 2019). These permeable FZs correspond to clusters of fractures partially open at the borehole scale and surrounded by a halo of hydrothermal alteration, identified in previous studies in the wells of Soultz and Rittershoffen (Vidal et al., 2018, 2017). Mineralogical studies of assemblages in fracture fillings indicate a complex polyphase circulation system (Dubois et al., 2000; Smith et al., 1998). 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), carbonates (calcite, ankerite, siderite), secondary quartz and sulfides (Ledésert et al., 1999; Traineau et al., 1992). The core of the FZ is composed of opened fractures and quartz veins, and the damage zone is composed of illitic minerals (Genter et al., 2000). Other secondary minerals could be present (carbonates, sulfates, sulfides, Fe-oxides). The nature, amount and shape of the secondary mineral seem to influence the thermal and hydraulic properties of the FZs. Alevizos et al. (2014) and Tung et al. (2018) suggested that occurrences of illite could enhance fault creeping, which can release fluid and trigger endothermic chemical reactions. The thermohydromechanical influence of clay minerals, particularly illite, on the fault movements at Soultz was already proposed by Meller and Kohl (2014). These endothermic reactions in permeable FZs could enhance the negative anomalies. The permeability of the FZs seems to be influenced by the crystallographic shape of the secondary automorphic quartz (Kling et al., 2017). Based on T and flow logs, most of the water circulation in the wells occurs in the first hundreds of meters of the granitic basement, where a high density of permeable FZs is observed as well as a high density of natural fractures: in the first 700 meters of the Soultz basement and between 200 and 400 meters of the Rittershoffen basement (Vidal and Genter, 2018).

3. MATERIALS AND METHODS

The study focuses on FZs in the granitic reservoir intersected by the wells GPK-1 and GPK-2 at Soultz-sous-Forêts and the wells GRT-1 and GRT-2 at Rittershoffen.

The first part of the study is the localization and characterization (geometry and secondary minerals filling) in the well. Acoustic image logs are an unwrapped 360º image of the borehole that gives the geometry of the fractures and its acoustic aperture at the borehole scale. Once the fracture network intersected by the well was identified, it was correlated to the following permeability indicators:

- Drilling mud losses and brine outflow are linked to permeable FZs (Dezayes et al., 2010; Evans et al., 2005; Genter et al., 2010, 2000; Sausse et al., 2010).
- The occurrence of alkanes, as well as other natural gases such as helium, CO_2 and radon, indicates permeable fracture zones (Aquilina et al., 1993; Vuataz et al., 1990).
- The mineralogical investigation of rock cuttings or core samples, when available, is an efficient method for identifying hydrothermally altered zones in the granite (Dezayes et al., 2010; Meller et al., 2014). Brine circulation through a permeable fracture zone leads to partial sealing by secondary geodic quartz and clay mineral deposits, which are easily detectable in cuttings by visual inspection, and in the laboratory by thin sections, fluid inclusion, isotopic measurements and XRD (Dubois et al., 2000; Fouillac and Genter, 1992; Ledésert et al., 1999; Smith et al., 1998). When cuttings are not available or reliable, gamma ray (GR) logging, which measures natural radioactivity, is a good indicator of hydrothermal alteration (Hooijkaas et al., 2006). In GR, the occurrence of geodic quartz is associated with sharp localized negative anomalies, whereas clay minerals, which are K-bearing minerals, are associated with positive anomalies that can extend several meters.

The second part of the study is the characterization of the thermal signature of the permeable FZ with T-logs. The T anomalies observed in a temperature profile are considered the most reliable of the permeability indicators (Bradford et al., 2013; Davatzes and Hickman, 2005; Evans et al., 2005; Vidal et al., 2017). T logs can be acquired at thermal equilibrium, i.e., after several weeks without well operations, or production or production. When T logs are acquired during production, a flow log can also be acquired, and the flow is measured based on the speed of the rotation of the helix (spinner tool). T logs acquired at equilibrium are acquired downward; T logs and flow logs acquired during production are acquired downward and upward in order to be sure to detect contributions with the rotation of the helix. T logs acquired during production allow for temperature estimation of the water circulating into the fracture zone following the methodology presented in Vidal et al. (2019). T log acquired in injection allow to detect contributions even if it doesn't indicate the temperature of the water circulations.

At equilibrium, T anomalies were identified primarily with T logs acquired before stimulation. Thermal equilibrium must not be influenced by cold mud or cold water stored in fractures after drilling and hydraulic operations. Poststimulation T logs were compared to pre-stimulation T logs. It is possible to observe some vertical depth shifts between T anomalies and fracture zones from core samples and image logs. These shifts could have several explanations. All logs were not acquired at the same time, and the process of depth matching among all logs is complicated. Moreover, temperature variations led to cable elongations that were not corrected for the well-logging data. The logs were shifted downward or upward based on the depths of the main open fractures observed in the acoustic logs.

4. RESULTS

4.1 Soultz-sous-Forêts

<u>GPK-1</u>

One of the major permeable FZ of GPK-1 is located between 3489 and 3496m MD (Dezayes et al., 2010). It is associated to mud losses but also occurrences of CH_4, CO_2 and radon (Vidal et al., 2018). GR presents a negative anomaly that corresponds to a quartz vein associated with fracture (Dezayes et al., 2010; Genter and Traineau, 1993). The FZ is surrounded by two major open fractures with a highly altered zone in-between (Figure 2). The deepest zone at 3496m MD strikes N170°E and dips 70° westward whereas the shallowest open fracture, located at 3498m MD strikes N160°E and dips 60º westward. In September 1996, during production at 10.8 L/s, a flow log and a T log were acquired. The first inflow of water into the well was observed at 3496 m MD, with a measured flow of 1.5 L/s. This inflow depth corresponds, with a negative T anomaly (148°C) in the T logs acquired during production. These anomalies are spatially correlated with the deepest open fracture. Then, several small positive anomalies are observed and associated with a flow increase at the same depth as the shallowest open fracture. All of these small anomalies are assumed to originate from the same fracture. Above this, the flow is 2.7 L/s, and the measured temperature is 149°C. Following the equation described in Vidal et al. (2019), the temperature of the water that arrives in this major fracture is approximately 150°C. At equilibrium (five months after the hydraulic tests), the water inflow through this permeable FZ is associated with a negative anomaly in the T log acquired in March 1993.

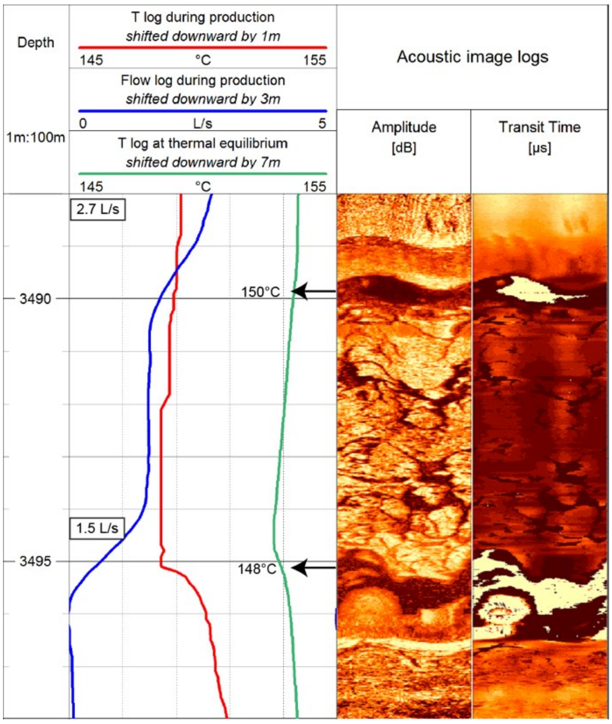

Figure 2 T logs from well GPK-1 at thermal equilibrium (Mar 1993, five months after the last hydraulic tests) and during production, with the corresponding flow log (Sept 1996, production test at 11 L/s). T and flow anomalies are associated with the open fractures observed in the acoustic image logs at 3490 and 3495 m MD, respectively. Arrows indicate inflows of geothermal water through the fractures. Depth is expressed in MD. The T logs and flow logs were shifted manually to fit the anomalies with fracture zones in all wells.

<u>GPK-2</u>

In the uppermost altered granitic reservoir, the well GPK-2 intersected two main permeable FZs. The first FZ is a cluster of fractures from 1869 to 1875 m MD mainly striking N0E with a westward dip and a main open fracture at 1870 m MD. It is associated with a sharp negative anomaly of GR with a minimum value of 232 gAPI at 1870 m MD. Based on cuttings, the granite presents a highly altered zone from 1840 to 1855 m MD (Genter and Tenzer, 1995). The T anomaly of +1°C is observed at 1860 m MD. The T anomaly is still observed after stimulations and deepening of the well but is negative (Figure 3).

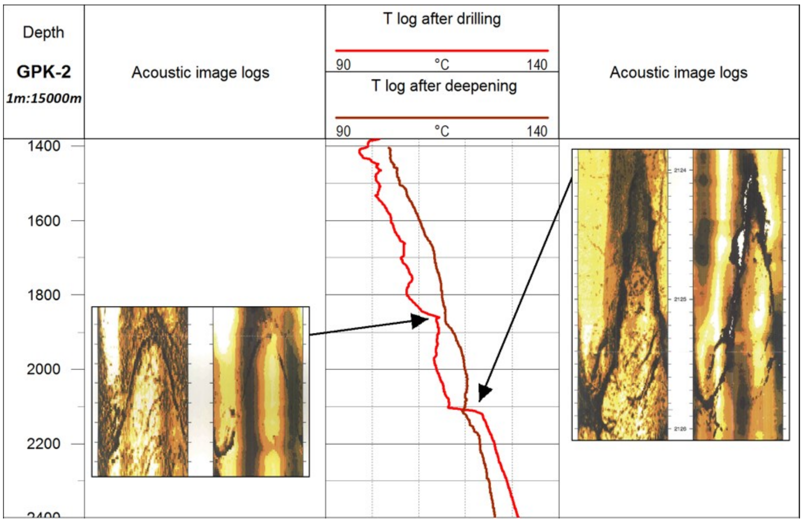

Figure 3 T logs from the well GPK-2, 3 days after drilling (Jan 1995) and after deepening (May 1999). T anomalies are associated with the open fractures observed in the acoustic image logs at 1870 and 2123 m MD, respectively. Arrows indicate inflows of geothermal water through the fractures. Depth is expressed in MD. The T logs were shifted manually to fit the anomalies with fracture zones in all wells.

Another FZ is intersected deeper with a main fracture striking N160°E and dipping 70°E at 2123 m MD and a 15-m thick damage zone above (Dezayes et al., 2010). It is associated with total mud losses from 2100 m MD. The temperature anomaly of +7°C is observed at 2123 m MD (Figure 3). The T anomaly is still observed after stimulations and deepening of the well but it is also negative. Unfortunately, the temperature of the water circulating in the well GPK-2 cannot be precisely calculated because flow logs and T logs acquired during production are not available.

4.2 Rittershoffen

GRT-1

The main permeable FZ of GRT1 extends from 2325 to 2368 m MD. Two major open fractures associated with mud losses were also identified. Cuttings of this FZ present euhedral quartz associated with local negative GR anomalies indicating occurrences of quartz veins. The deepest open fracture is located at 2368 m MD, strikes N175°E and dips 65° westward. This fracture controls 2/3 of the total flowrate and is at the interface between highly altered and fractured granite above and low altered granite below (Vidal et al., 2017). Thus, this fracture permits the first inflow of water into the well. Surprisingly, the flow log is not consistent with this observation and is thus considered unreliable for the evaluation of the absolute flow associated with the fractures in the well. The flow anomaly is associated with a T anomaly (+3°C) at 2364 m MD (Figure 4). A second T anomaly (+5°C) at 2350 m MD is observed. This positive T anomaly is not clearly associated with an open fracture but is associated with a cluster of thin fractures. However, the calculation of the water temperature at this depth is not possible because the flow log is not reliable. At equilibrium, the pre-stimulation log indicates a large negative T anomaly, whereas the poststimulation T log indicates two negative anomalies that correspond with those observed during production.

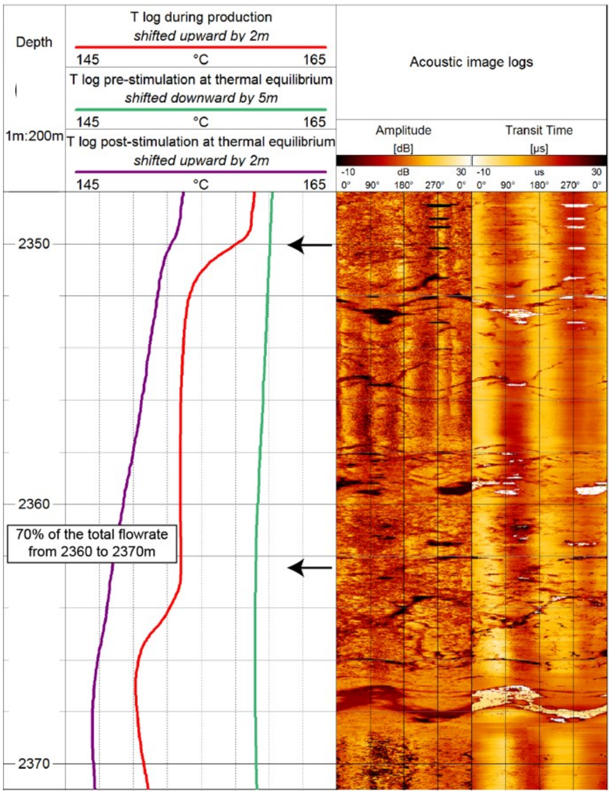

Figure 4 T logs obtained from well GRT-1 during production (Jan 2013, airlift production), at thermal equilibrium pre-stimulation (Apr 2013, four months after hydraulic tests), and poststimulation (Dec 2013, five months after hydraulic stimulation). T anomalies are associated with open fractures observed in image logs between 2350 and 2370m MD. Arrows indicate inflows of geothermal water through fractures. Depth is expressed in MD. T logs and flow logs were shifted manually to match anomalies with fracture zones.

The shallowest open fracture of the FZ, at 2326m MD, strikes N20°E and dips 50° westward (Vidal et al., 2017). Although mud losses were observed during drilling operations, no T anomaly was observed during production at this depth. A small negative anomaly is observed in the poststimulation T log.

GRT-2

In the uppermost altered granitic reservoir, the well GRT-2 intersected two main permeable FZs from 2534 to 2540m MD and from 2766 to 2800m MD. They are both composed by open fractures at the borehole scale, which mainly strike N170°E and dip westward, surrounded by halo of alteration (Vidal et al., 2017). They are associated to mud losses and occurrences of methane for the shallowest one. They are both associated with positive T anomalies which is quite surprising because they are the only positive anomalies at equilibrium observed in T logs of the URG. However, no injection of cold water was realized in the well before the acquisition of the T log and thus, the anomalies are considered reliable. They indicate water inflows hotter than the surrounding rock formation. Unfortunately, the temperature of this water cannot be precisely calculated because flow logs and T logs acquired during production are not available. Both anomalies are associated with open fractures.

5. DISCUSSION

5.1 Interpretation of T anomalies at the borehole scale

The deep permeable FZ in GPK-1 presented in Figure 2 corresponds to the first inflow of water into the well. The first inflow of water into the well is at 148°C through a fracture at 3496 m MD (Figure 5). The negative anomaly in the production T log is explained by an inflow of water colder than the deeper reservoir during production. The positive anomaly described above is interpreted as the inflow of water from a fracture at 3489 m MD, which is hotter (150°C) than water from the fracture at 3496 m MD (148°C). At thermal equilibrium, this FZ is associated with a negative anomaly because the water inflows have temperatures of 148°C and 150°C and are probably colder than the temperature of the deep granite at equilibrium.

T log in production in GPK-2 is not available. There is an inversion of the polarity of the T anomalies associated with permeable FZs at 1860 and 2123m MD (Figure 3). After drilling they appear positive because the reservoir is probably cooled by the drilling operations. Several months after, after the deepening, the top of the granitic reservoir reached the equilibrium. The well has heated up and the global T profile is shifted, so that finally it is hotter than after drilling and the T anomalies appear negative. However, the temperature of these anomalies didn't change (114ºC), it's the temperature of the reservoir that rose above the temperature of the anomalies.

The deep permeable FZ in GRT-1 presented in Figure 4 also corresponds to the first inflow of water into the well. Positive T anomalies are observed in the bottom part of the FZ at 2365 and 2350 m MD because geothermal water that comes from the fractures is hotter than the water coming from the underlying reservoir. At thermal equilibrium, these hot water inflows are no longer observed, but the negative T anomaly does not suggest that hot water does not circulate. This means that the circulating water is probably colder than the reservoir at equilibrium. These fractures correlate with a flow anomaly.

The well GRT-2 exhibits the only two positive T anomalies at equilibrium observed in the granitic reservoir of Rittershoffen. Positive T anomalies are probably less common than negative T anomalies at equilibrium because the reservoir at equilibrium is generally hotter than the circulating water. Fractures are direct paths for cold mud or water during drilling and hydraulic operations and thus cool faster than the rest of the rock formation. The greater the quantity of cold water that is injected, the fewer positive anomalies visible. Because well GRT-2 was not stimulated, positive anomalies are probably more common in that well than in the stimulated wells GRT-1, GPK-1 and GPK-2.

In the recently drilled geothermal well, GIL-1, of the Illkirch geothermal well (Strasbourg) T logs were acquired in injection and presents seven T anomalies after drilling operations in the granitic reservoir (Glaas et al., 2020). Because T logs were not acquired in production or under T equilibrium as at Soultz and Rittershoffen, T anomalies cannot be interpreted in terms of temperature or polarity. However, they all match open fractures, and thus, definitely indicate circulations in the reservoir.

As observed by Evans et al. (2005), temperature flux and geothermal fluid flow are intimately linked. T logs are better tools than flow logs for examining water circulation because T logs are more sensitive to small water inflows than flow logs, which require massive water inflow to produce an observable modification in the rotation speed of the helix. However, the estimation of the absolute water temperature circulating in a fracture requires a reliable associated flow log, which is often not available.

5.2 Hydrothermal convection in the granitic fractured reservoir

Convective regimes are associated with geothermal reservoirs in the URG. In the hydrothermally altered granitic reservoirs, geothermal gradients are below 20 °C/km in general. This is interpreted as hydrothermal circulations through the fracture network associated with large-scale normal faults mainly striking N-S and dipping westward (Baillieux et al., 2014). With their relatively important vertical displacement (> 200 m), these faults are interpreted as potential permeable drains for geothermal resources. Even at equilibrium, the convective regime observed in the T log is disturbed by discrete T anomalies that are interpreted as the T signature of the permeable FZs. These permeable FZs are composed by open fractures of several centimeters wide inside the FZs probably interconnected to each other over short distances, leading to a rather complex 3D organization that has channelized the water circulation (Sausse and Genter, 2005)

The polarity of the T anomalies cannot be linked to the orientations and dips of the associated FZs at the borehole scale. Borehole data showed that T anomalies are negative or positive independently of the fracture orientation or dips. The mineral precipitations could influence the recurrence of negative anomalies (Figure 5). As modeled by Gentier et al. (2004), during cold injection, thermal microcracking of quartz within the FZ is observed, which creates preferential flow paths and thus leads to preferential cooling in these fractures. All permeable fractures are associated with quartz veins, which could enhance the thermal effect of cold reinjection through the FZs (Figure 2, 3 and 4). Genter et al. (2010) proposed this interpretation where the negative T anomalies in T logs at equilibrium result of cooling of the FZs at Soultz. However, the dataset presented in this study suggest another interpretation where the negative anomalies indicate that the circulation of water is colder than the surrounding formation.

Negative T anomalies at equilibrium are observed more often than positive ones in the wells of the URG, because the negative anomalies are linked to the contrast between the temperature of the fluid circulating through the FZs and the temperature of the reservoir at equilibrium, which is generally hotter than the circulating water. Especially after drilling or injection operations, FZs are preferentially cooled. During production, a positive T anomaly indicates an inflow of water hotter than the mix of water coming from below (Figure 5). At equilibrium, this anomaly could be positive if the geothermal water coming from the fracture is hotter than the surrounding rock formation or negative if the geothermal water is colder than the surrounding rock formation. However, equilibrium could be difficult to identify depending on the volume of cold water previously injected and the time since the last injection.

T logs acquired during production are representative of the mix of water present during circulation, whereas T logs at thermal equilibrium reflect the temperature of the water leaching through the FZs relative to the temperature of the surrounding rock formations. Inside a permeable FZ, geothermal water can circulate at different temperatures through different partially open fractures, representing multichannel pathways for geothermal fluids, as observed in GPK-1, where the water coming from the upper fracture is hotter (Figure 5). In this case, water coming from fractures less than 10 m apart circulates at different temperatures, which is surprising because circulations coming from narrow fractures should reach a state of equilibrium and a homogeneous temperature. Water may circulate through the FZs too fast to reach equilibrium. From the dataset presented in this article, the velocity and direction of these circulations cannot be determined.

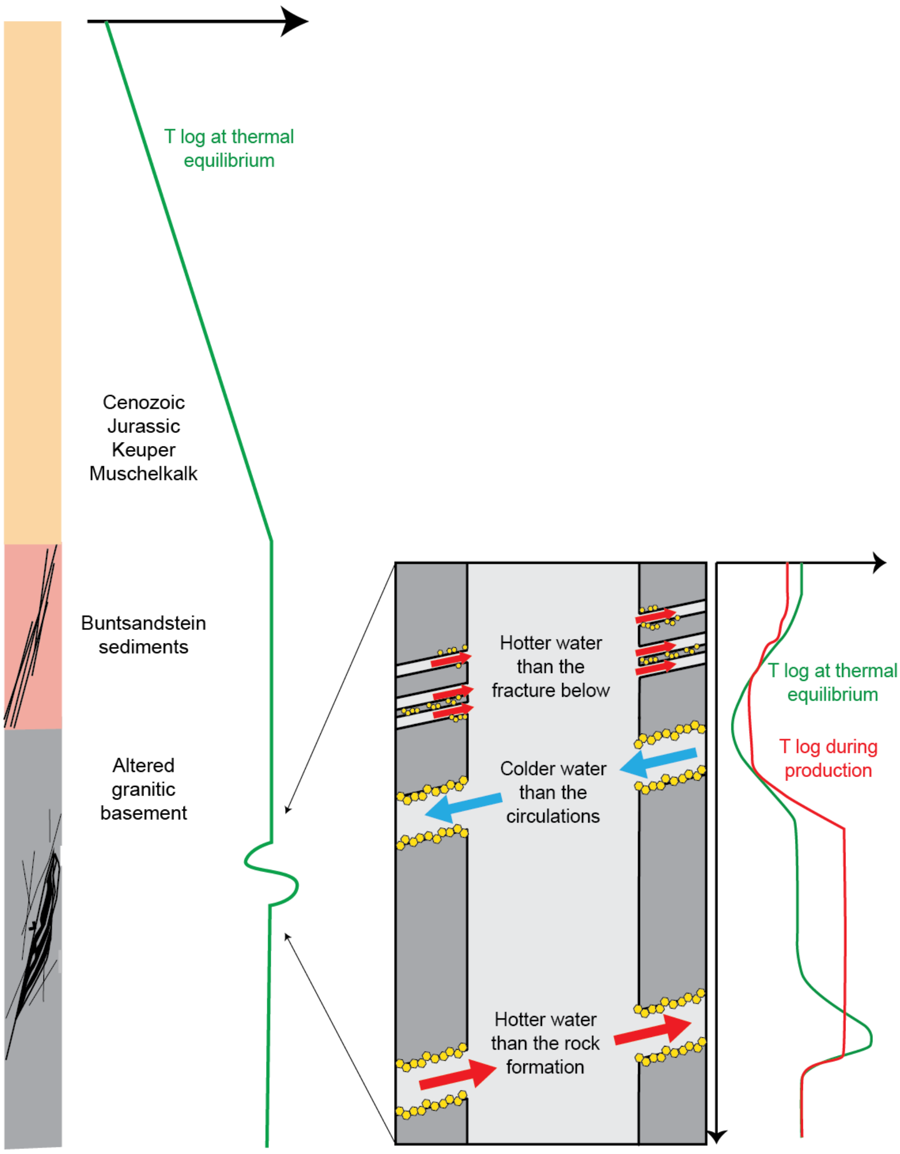

Figure 5 T signature of permeable FZ in the altered granitic basement associated to a convective regime

Structural and mineralogical observations in Rittershoffen wells indicate that the hanging wall of the Rittershoffen fault correspond to the highest level of hydrothermal alteration, but also the highest natural permeability (Vidal et al., 2017). In GRT-1, all T anomalies are observed in the first 200m of the granitic basement that correspond to the hanging wall. This hanging wall is more hydrothermally altered than the footwall that could explain the highest permeability. The configuration of GRT-2 is slightly different because it is drilled directly through the fault zone. T anomalies are also observed below the intersected fault plane but the all positive anomalies are observed above, in the first 700m of the granitic basement that corresponds to the highest naturally permeable reservoir.

At Soultz, the localization of T anomalies indicate that the highest permeable reservoir is intersected in the first 700m of the granitic basement. The structural configuration of the Soultz wells and the local faults are more complex and the identification of the hanging wall is not trivial as in Rittershoffen.

In the project of Illkirch, GIL-1 intersects the targeted fault zone at the interface between the fractured sandstones and the granitic basement. The most permeable granitic reservoir was intersected through more than 400m. Studies of the hanging wall located on the sandstones is necessary for further conclusions on the natural permeability of the reservoir. However, the link between high alteration and permeability in the hanging wall are also observed for fault zone that affects sedimentary formation (Brogi, 2008).

6. CONCLUSION

The hydraulic yields of the reservoirs are intimately linked to the thermal regimes. Hydrothermal circulations in the deep sedimentary cover and in the hydrothermally altered granitic basement are visible from thermal profiles in geothermal wells in the URG. Moreover, deep geothermal wells at Soultz, Rittershoffen and more recently at Illkirch intersected fracture zones associated with thermal anomalies that are either positive or negative. These T anomalies are interpreted as the thermal signature of the permeable FZs. The comparison of T logs acquired in production and at thermal equilibrium provides a new interpretation of temperature anomalies. Based on these data and on available flow logs, the temperature of water coming from partially open fractures was estimated. The study shows that geothermal water could circulate at different temperatures and in different fractures a few meters apart within the same FZ, which suggests a new interpretation of T anomalies in rather complex hydrothermally altered and fractured zones.

At temperature equilibrium, T anomalies are positive or negative with respect to the temperature of the surrounding rock formations. Because the surrounding formations are often hotter than the fractures, especially after drilling or injection operations as permeable fractures are direct paths for fluid and thus cool faster than the surrounding rocks, negative anomalies are more often observed than positive ones. Moreover, it was observed that all permeable FZs are composed of several partly open fractures associated with secondary quartz. The occurrence of quartz, because of its thermal cracking behavior, could also enhance the cooling effect observed in the T logs.

In contrast, during production, anomalies are positive or negative with respect to the mix of water circulating below the fracture and not with respect to the surrounding formation. Therefore, T anomaly polarity could change over time depending on the equilibrium state.

The occurrences of the discrete T anomalies in the T log indicate that the well intersected the permeable fracture network and this is crucial for geothermal projects in such young graben tectonic context. The implementation of T logs that are cheap and reliable tools is very useful for characterization of the hydrothermal circulations at the borehole scale.

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