Permeability in deep-seated granitic rocks: lessons learnt from deep geothermal boreholes in the Upper Rhine Graben
Perméabilité des roches granitiques profondes : quelles leçons des forages géothermiques profonds réalisés dans le Fossé rhénan supérieur

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I. INTRODUCTION

The Upper Rhine Graben (URG) is characterized by a series of geothermal anomalies related to natural hydrothermal convection circulating within the fractured crystalline basement. Based on deep drilling operations in Northern Alsace ranging between 2.6 and 5 km depth, occurrences of hydrothermal fluid circulations have been evidenced in the granitic basement in framework of pilot research and industrial geothermal projects. In those geothermal wells, bottom hole temperature ranges from 170 to 200°C for wells drilled to 2.6 and 5 km depth respectively. Water bearing fractures characterized by geothermal brines (TDS 100g/L) have been observed in hard-rocks such as Triassic clastic sediments as well as in Paleozoic crystalline basement. Geological and structural evaluation of these fracture zones properties in terms of alteration, permeability, flow circulations introduce new concepts for industrial projects in the URG. Thus, the deep-seated fractured sediment-basement interface of the URG is the main geological hard rock target for new geothermal projects planned.

II. GEOTHERMAL PROJECTS IN THE URG

The URG is a geological structure characterized by several thermal anomalies in the French side like in Rittershoffen and Soultz-sous-Forêts (Alsace) as well as in the German side, in Insheim and Landau (Rhine-Palatinate) (Figure 1). These geothermal anomalies are related to natural brine advection inside a nearly vertical multi-scale fracture system cross-cutting both deep-seated Triassic sediments and Paleozoic crystalline basement (Kohl et al., 2000; Pribnow and Clauser 2000, Genter et al., 2010). Post-Paleozoic sediments in this Tertiary basin host oil field widely exploited in the past by deep wells or galleries in which abnormal high temperature gradients were measured (Haas et Hoffmann, 1929). Since 1988, several deep geothermal wells were drilled in order to develop a new technology for electricity production from basement rocks called Hot Dry Rocks (Gérard et Kappelmeyer, 1987). Those wells were originally designed for creating artificial heat exchanger in such poorly permeable rocks by hydraulic stimulation. However, natural permeability was systematically observed in fractured zone/faulted zones which was significantly improved by applying various Thermo-Hydro-Mechanical and Chemical (THMC) treatments renamed as Enhanced Geothermal System or Engineered Geothermal System (EGS).

Started in 1986, the ***Soultz-sous-Forêts project*** explored during more than 25 years the experimental geothermal site by drilling five deep wells and one fully cored exploration well (Dezayes et al., 2005). The first borehole, GPK-1, was drilled to 2 km depth in 1988 and deepened to 3.6 km depth in 1992. In 1995, the second geothermal well, GPK-2, was drilled to 3.9km depth into the granitic reservoir. In the beginning of the 21st century, the geothermal triplet (GPK-2, -3, -4) was drilled in order to develop a deep granitic reservoir at 5 km depth where a bottom hole temperature of 200°C was achieved. Several old oil wells were deepened to the top of the granitic basement (1.5 km depth) in order to install down-hole seismic sensors for conducting in-situ micro-seismicity monitoring during drilling, hydraulic stimulation or multi well circulation tests.

Three vertically distributed reservoirs were developed and investigated between the top basement (1.5 km) and the bottom holes (5 km). Several hydraulic and chemical stimulations were done with variable hydraulic improvement (Nami et al., 2008, Schill et al., 2015). In the deepest reservoir at 5 km depth, production flow rate with a down-hole submersible pump produces 24 L/s at 165°C. Recent studies based on drilling data revealed the occurrences of permeable fractures embedded within the deep-seated Triassic sediments of the Soultz wells but which were never exploited (Vidal et al., 2015).

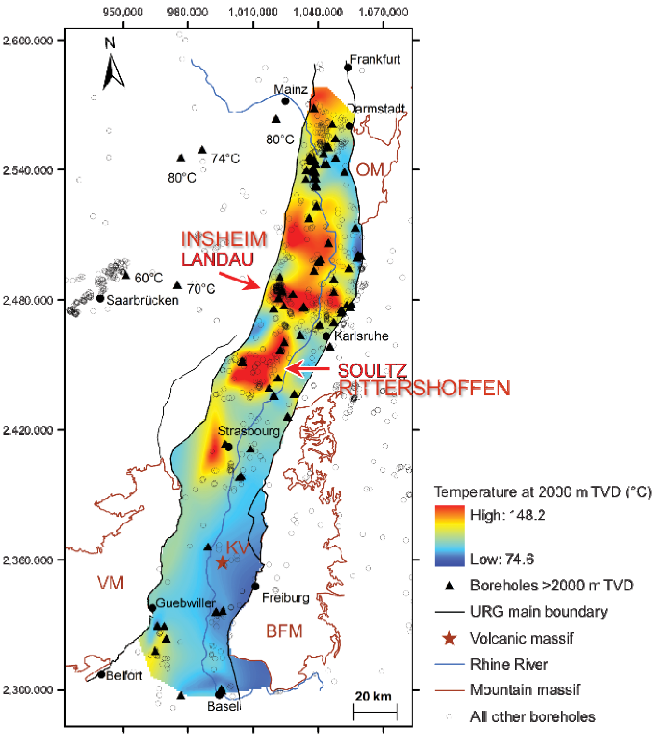

Figure 1 - Temperature distribution at 2000 m depth in the URG (Baillieux et al., 2013)

The ***Landau project*** was based on the lessons learnt at Soultz by targeting the sediment-basement interface where the permeability was higher than in the 5k m Soultz wells. The geothermal wells Gt La1 and Gt La2, were drilled to approximately 3.3 km depth in 2005 and 2006 respectively (Schindler et al., 2010). Both wells targeted a fractured reservoir located in the deep clastic sediments and the fractured crystalline top basement. The production well provided a temperature of 160°C and a flowrate of 70 L/s. Only the second well, used as an injection well, needed to be hydraulically and chemically stimulated in order to improve its hydraulic performance.

The ***Insheim project*** was also based on a multi-formations reservoir concept. The two wells, GTI-1 and GTI-2, were drilled to 3.8 km depth in 2008 and 2009 respectively. The first well shows a temperature is 160°C with a flowrate of 85 L/s. Fractured permo-triassic sediments and porphyritic basement compose the actual open-hole section (Baumgartner et Lerch, 2013).

The ***Rittershoffen project***, made of two deep boreholes drilled to about 2.5 km depth, targeted a fractured reservoir in lower Triassic sediments and in granitic basement interface. Successful thermal, hydraulic and chemical stimulations of the injection well improved significantly its poor initial hydraulic injectivity allowing reaching a valuable post-stimulation performance (Baujard et al., 2015). The second inclined well drilled down to 3.5 km depth, shows a production flow rate compatible with industrial conditions, e.g. at least 70 L/s and 160°C and thus, was not stimulated.

Figure 2 - Chronology of geothermal projects and associated deep wells in the Upper Rhine Graben

III. THE SOULTZ GEOTHERMAL PROJECT

III. 1 Geological Setting

The Soultz geothermal pilote site is located on a horst structure (Figure 3). Deep geothermal boreholes penetrated a sedimentary pile of 1400 m thick made of Tertiary and, eroded Jurassic and Permo-Triassic sediments. The uppermost part of the Paleozoic granitic basement is affected by a paleo-weathering alteration inducing reddish colored granite on approximately 150 m thick. Deeper, grey pink MFK rich porphyritic granite unit is locally affected by intense hydrothermal vein alteration related to successive paleo-circulation events. Below, between 4800 m depth and the bottom depth, a fine-grained two-mica granite occurs.

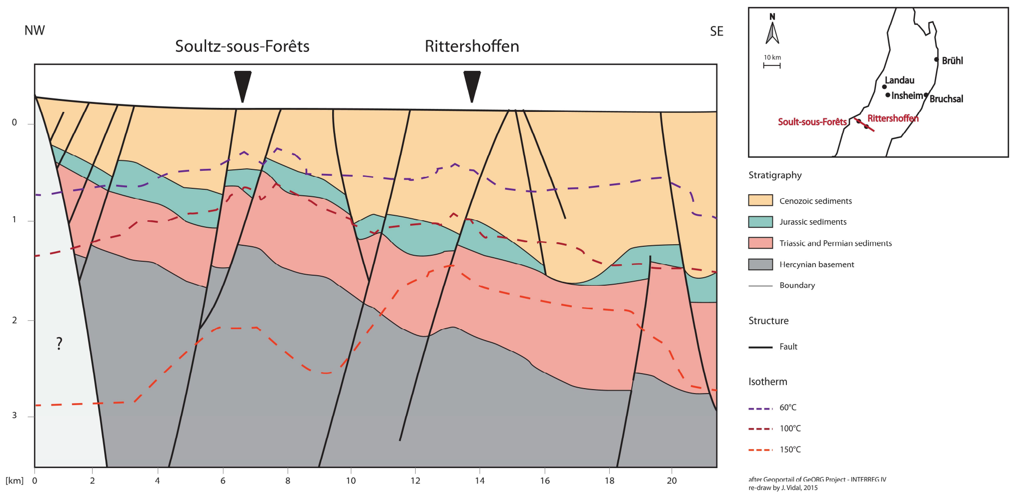

Figure 3 - Geological interpretation through Soultz-sous-Forêts and Rittershoffen geothermal sites

Structural investigations based on various geological and geophysical methods (continuous coring, borehole image logs, Vertical Seismic Profiling, seismic profiles) clearly evidenced the occurrence of a multi-scale fracture network from large-scale normal faults to minor fractures (Dezayes et al., 2010). They represent the main pathway for the geothermal fluid. Detailed fractures survey in the Triassic and Permian sandstones as well as in the granite basement shown that natural fractures systematically exhibit hydrothermal secondary deposits such as geodic quartz, clay minerals, carbonates (calcite, dolomite, ankerite), sulfates (anhydrite, barite) or sulphides (galena, pyrite) (Figure 3). Based on borehole image logs, temperature profiles and spinner logs collected in the wells, a rather limited number of fractures or hydrothermally altered and fractured zones match spatially with discrete outflow anomalies (Evans et al., 2005; Vidal et al., 2015).

Detailed structural studies on 1200m length of continuous Soultz core on both Triassic sandstone and Paleozoic granite showed a higher average fracture density in granite compared to sandstone with 3,8 fract/m against 0.77 fract/m respectively (Genter et Traineau, 1996, Genter et al., 1997). In the granite, low fracture intervals (1520 to 1620 m and 1910 to 2040 m with 0.7 to 1.3 fractures/m, respectively, on average) coexist with high-fracture intervals (1770 m to 1840 m with 4.0 fractures/m on average) and also with intense-fracture zones (1420 to 1460 m, 1620 to 1660 m, 2050 to 2080 m, and 2150 to 2180 m with 9.0 fractures/m on average). The intense fracture zones correlate with fault zones that developed hydrothermal alteration, and low-fracture intervals correspond to massive unaltered granite (Genter et al., 2000). Moreover, it was clearly demonstrated a higher fracture density at the top of the granitic basement between 1420 and 1460m due to the superimposition of sub-vertical fractures with nearly horizontal joints. Occurrence of this flat jointing was interpreted as a consequence of the paleo-emersion event affecting the top crystalline basement during Permian times. This paleo-weathering event is responsible for the whole reddish color of the top granite basement correlated to a leaching of primary magnetic and ferro-magnesian minerals (magnetite, biotite) as it was evidenced be magnetic susceptibility survey (Rummel, 1991).

Even though the Soultz wells cross cut several thousand of natural fractures locally clustered within fractured zones, only a few of them clearly shown some evidences of initial permeability during drilling operations. They generally correspond to hydrothermally altered and fractured zones showing a fracture cluster organization (Figure 3). Thus, the initial permeability is intimately linked to these fractured zones. In the granitic section of the site, between the top basement and 5 km depth, fracture density decreases with the depth excepted when the borehole locally cross cut fractured zones (Dezayes et al., 2010).

Matrix permeability determined from laboratory measurement conducted on unaltered rock Soultz samples ranges between 10^{-18} to 10^{-21} m^2 (Hettkamp et al., 1999). Some of the permeable naturally hydrothermally altered zones intersected by the boreholes had transmissibilities between 0.1 and 50 d m (darcy meter; 1 d m = 10^{-12} m^3) demonstrating that much more than 90 % of the water in the granite is carried by a few highly permeable faults and not by the joint network (Jung, 2013). Due to good temperature conditions in the granitic basement but rather low and localized natural permeability in the granite, all the Soultz wells were hydraulically and chemically stimulated (Nami et al., 2008). Based on a review of various hydraulic tests (injection, production, stimulation, circulation), it has been shown that three vertical reservoirs were developed lying at 2, 3.6 and 5 km depth (Schill et al., 2015). As fracture density which shows a general decreasing with depth, it was observed that natural injectivity of the three reservoir levels is quite low, and decreases with increasing depth from $9 \cdot 10^{-2}$ l/s/bar in the upper reservoir at GPK1 to $1\text{-}2 \cdot 10^{-2}$ l/s/bar in the deep reservoirs at GPK2 and GPK4. The highest natural injectivities never observed at Soultz match with total mud losses at 2100-2120 m during GPK2 drilling (Figure 3). Jung (1991) proposed a pre-stimulation injectivity of 3·l/s/b for this fractured zone.

III. 2 Geothermal Setting and Natural Fracture Zones

Among the main outcomes from deep Soultz boreholes, accurate measurement of the temperature profiles from surface up to 5000 m provided absolutely unique and valuable information (Figure 3). The thermal profile shows two zones where the conductive regime dominates (0-1 km, 3,5-5 km) and an intermediate zone (1-3.5 km) where advection and / or convection dominate (Figure 3). The latter is indeed the most intensely fractured zone and show some evidence of natural water, very salty (100g/L) circulating in a channelized network of fractures and sub-vertical faults. These brines transport heat to the surface and are the source of the thermal anomaly (Genter et al., 2010).

The thermal profile shows so clearly that it was not necessary to drill 5 km if one seeks a geothermal resource type "hydrothermal". Indeed, the 1000-3500 m zone shows an almost zero geothermal gradient and therefore almost constant temperature around 150°C (Figure 3). It is therefore interesting to preferentially drill at the top of this zone not only to reduce drilling costs (1500-2000 m in the fractured granite in the case of Soultz), but above all to increase the probability of overlap permeable fractures that will ensure the design flow for future exploitation. This new approach has a direct impact on the economic balance of projects. The supplied thermal power is proportional to the production rate and the temperature differential, it is no longer necessary to look 200°C at 5000 m, it is better, in fact, to target a heat resource at 150°C between 1500 and 2000 m depth with a good permeability allowing higher production rates. This feedback was applied to the Rittershoffen industrial project where drilling had penetrated only 500 m inside the crystalline basement fractured.

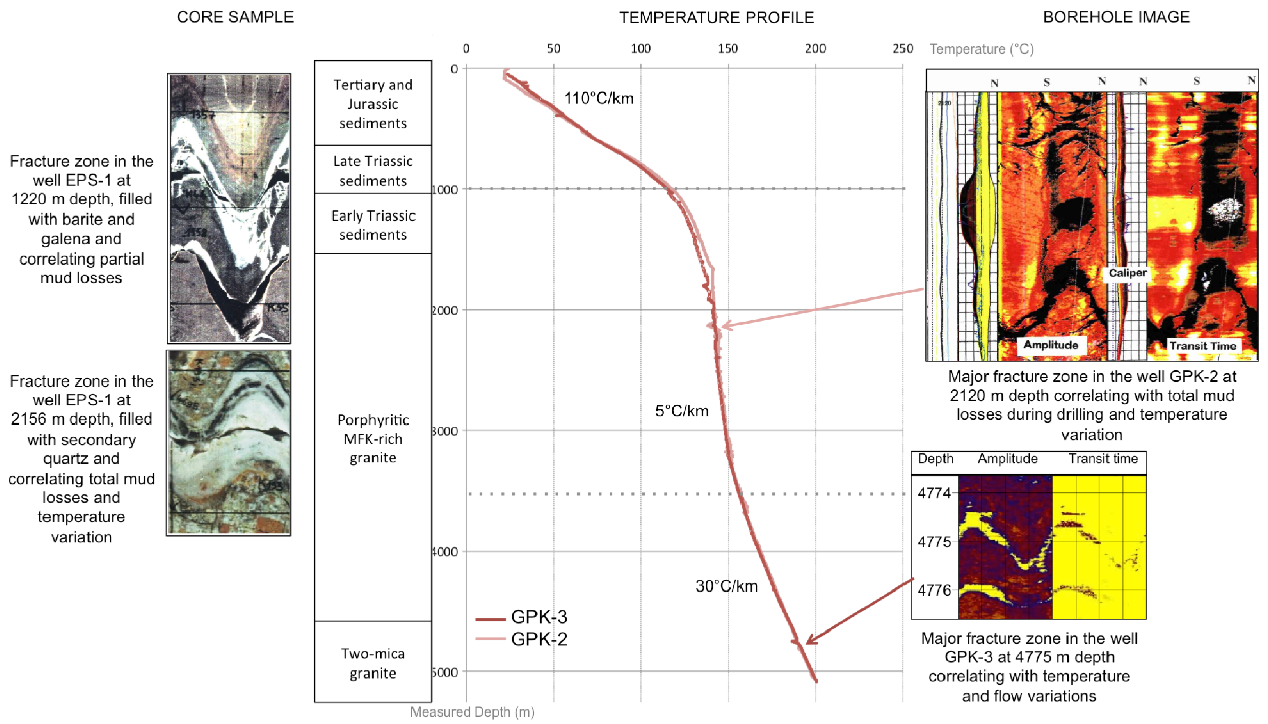

Figure 3 - Borehole images of major fracture zones in the geothermal wells GPK-2 and GPK-3 associated with thermal anomalies. Example of fracture zones from cored well EPS-1.

The thermal profiles of the Soultz wells show local thermal anomalies (Figure 3). Permeable fractured and altered zones are cooled by the invasion of drilling mud or fresh water during hydraulic stimulation operations. Fractures in the granitic basement have a negative thermal signature visible even several months after hydraulic operations.

The assumptions of negative anomalies as major fracture zone signatures may be verified if other parameters as mud losses, spinner logs or borehole images are recorded. The second unit is disturbed by several thermal anomalies and the bigger one is located at 2120 m depth. The borehole image presents a fracture zone at the same depth with a caving of the well. This zone is visible on amplitude data and on transit time data and thus is opened at least at the borehole scale. During drilling of the well, total mud losses were observed by the driller and indicate a permeable fracture zone.

In the last unit, only one sharp thermal anomaly is visible at 4770 m depth on the thermal profile of GPK-3. This zone is well observed on the borehole image and controls 70% of the flowrate in the well. This is the only permeable fracture zone with a thermal signature in the deeper part of the granitic reservoir.

IV. THE ECOGI Geothermal project

IV.1. Geological context and target

Following the Soultz experience, the ECOGI geothermal project was initiated in 2011. It is designed is to deliver a power of 25 MWth at the "Roquette Frères" bio-refinery in Beinheim in order to cover around 25% of the process heat needed by this industrial site. The drilling site is located in Rittershoffen, 6 km east of Soultz-sous-Forêts, in Northern Alsace, France. The project is supported by the "ADEME", the "Conseil Régional d'Alsace" and "SAF Environnement". ECOGI is a joint venture; the shareholders are "Electricité de Strasbourg" Group, "Roquette Frères" and a public institution "Caisse des Dépôts et Consignation".
Based on pre-existing 2D seismic lines, a fractured/faulted zone dipping westward and located closed to the transition between the Triassic sandstones (Buntsandstein) and the top basement (Carboniferous granite) has been identified as a geothermal target for wells GRT-1 and GRT-2. This local normal fault, which is roughly oriented N-S, shows an apparent vertical off-set of 200 m and limits the western part of the Rittershoffen horst structure. Based on old oil wells but also on the experience of the Soultz-sous-Forêts results, it was assumed that this local fault could present favourable permeability conditions.
The first vertical well GRT-1 (2580m MD) has been drilled in winter 2012-2013 and the second deviated well, GRT-2 (3200m MD), has been drilled in spring 2014. Seismic data were acquired in summer 2013 in order to secure the target location. Both well target the same local normal fault acting as a fractured zone. At target depth, the horizontal distance between wells is around 1200m.

IV.2. GRT-1 and GRT-2 hydraulic properties

Geological monitoring and mud logging operations during drilling of well GRT-1 show two main zones of drilling mud losses, corresponding to fracture zones, in the Secondary sediments (Muschelkalk) and in the crystalline basement. No major mud loss zone was identified in the Secondary sediments during drilling of well GRT-2, but total mud losses have been observed in the crystalline basement.
Pumping tests based on air-lift and artesian flows realised in both wells indicate productivity and injectivity indexes around 2-3 l/s/bar at nominal flowrate (70 l/s). Associated transmissibilities were estimated around 2 d m in GRT-1 and to more than 25 d m in GRT-2. No clear hydraulic boundary could be identified with the pumping test interpretations. Flow logs realized during production tests clearly show that fluid flow zones are a few tens of meter wide in both wells (open sections are 600m long for GRT-1 and more than 1000m long for GRT-2). A pressure interference test and a tracer test were carried out between GRT-1 and GRT-2. These tests showed a hydraulic and mass connexion between wells. Due to a low hydraulic diffusivity, the hydraulic response time between wells is rather short (a few hours), and tracer breakthrough was observed after 10 days of circulation, which is much more than in Soultz, where tracer breakthrough was observed after less than 4 days only, with lower circulation flowrates.

IV.3. Hydrothermal system behavior

Extensive logging programs have been realised in both wells. Unfortunately, most of the logging tools could not go through the open section of GRT-2 as this well is significantly deviated. Bottom hole temperature in GRT-1 is around 163°C, and bottom hole temperature in GRT-2 reaches 177°C. Temperature logs in both wells (Figure 4) show that temperature distribution below the clays of the Keuper (late Triassic) is strongly dominated by advective and/or convective processes, whereas the linear temperature distribution above this layer suggests a purely conductive temperature regime. This tendency appears here more clearly than in Soultz-sous-Forêts, which seems to indicate that fluid flows at depth in the region are driven by regional fault zones.

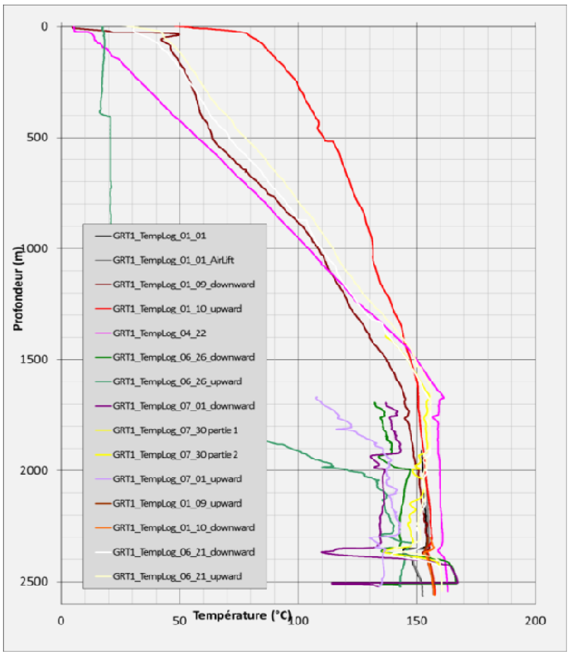

Figure 4 - Temperature logs in GRT-1. Depths are given in MD

Water flowing zones in the reservoir are clearly correlated with temperature anomalies. Interestingly, temperature logs around some flowing zones show a positive anomaly at the top of the zone and a negative anomaly at the bottom. It has been showed (see for example Magnenet et al., 2015) that large scale (kilometer scale) convection processes can occur in fault planes. Observations made on these temperature profiles could indicate even more complex convective processes occurring in these fault zones, like small scale convection cells located within a given fault zone width.

V. LESSONS LEARNED FROM THE PILOTE GEOTHERMAL PROJECT

All the industrial geothermal projects located in the Upper Rhine Graben derived from the Soultz research site (Insheim, Landau, Rittershoffen) reached their geothermal target in terms of temperature and permeability. They demonstrated the occurrence of a geothermal resource related to the natural fracture system mainly located at the interface between the deep Triassic sediments and the top of the crystalline basement. Due to low initial permeability conditions, some geothermal wells were hydraulically and chemically stimulated whereas other wells were naturally permeable enough to avoid any stimulation. Therefore, the occurrence of this shallower geothermal resource has a serious positive impact on the drilling costs. The newly drillholes done at Rittershoffen confirmed permeability related to natural fractures located within Triassic sedimentary layers (Muchelkalk, Buntsandstein). Observations made on temperature logs in Soultz as well as in Rittershoffen seem to indicate that a no flow boundary is located at the basis of the Keuper layers (i.e. at the top of the Muschelkalk), and that hydraulic flows below these layers are dominated by complex convective and / or advective processes.

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