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New stratigraphic interpretation of the Soultz-sous-Forêts geothermal wells based on Rittershoffen (Upper Rhine Graben, France)

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ABSTRACT

In Northern Alsace, the Soultz-sous-Forêts pilot project for power production is the first on-going geothermal site. In this geothermal project, most attention was focused on the basement and the sedimentary cover/basement interface. It follows that the sedimentary part from the drilling (around 1.4 km thick) was never really investigated. The main challenge of this work is therefore to re-interpret the old wells' data in order to give a precise and detailed chrono-lithostratigraphic log for GPK-1 and GPK-2 especially in their sedimentary part. These new investigations of the GPK's wells have been possible thanks to the new data collected in the recent geothermal wells at Rittershoffen (GRT-1 and GRT-2, spaced of 6.5 km from Soultz-sous-Forêts) characterized by a quiet complete stratigraphic succession. Both sites have been explored by deep drilling operations aiming to exploit the heat extracted from a deep granitic basement (Paleozoic) covered by a stack of 2.2 km thick sedimentary rocks (Mesozoic to Cenozoic). Thus, the Rittershoffen's chrono-lithostratigraphic logs have been used as a baseline in order to interpret the sedimentary succession from GPK-1 and GPK-2. As a conclusion, the GPK-1 and GPK-2 well logs will be paralleled for stratigraphic comparisons. Four major faults were highlighted. This extended abstract summaries the research reported in Aichholzer et al. (2016).

1. INTRODUCTION

Due to the "West European Paleogene Rift System" the geothermal gradient is abnormally high in Northern Alsace (the temperature highlighted 50 °C at 400 meters deep) (Haas et Hoffmann 1929). These high temperatures in the underground triggered different geothermal projects in Alsace region which is located in the north-eastern part of France (fig. 1). The Upper Rhine Graben (URG) is therefore one of the most studied region in Europe, mainly for petroleum exploitation and recently for geothermal applications like on the French side with the Soultz-sous-Forêts geothermal pilot site and the Rittershoffen industrial geothermal one. Between 2012 and 2015, at Rittershoffen, two new geothermal boreholes GRT-1 and GRT-2 were successfully drilled up to the granitic basement, final depth at 2562 m and 2707 m vertical depth respectively (Baujard et al. 2015). This doublet was the subject of particular attention in the acquisition of a very precise stratigraphic profile (Aichholzer et al. 2015, 2016). GRT-1 and GRT-2 have been used as a reference well for the chrono-lithostratigraphic analysis which aims to reinterpret GPK-1 and GPK-2 Soultz-sous-Forêts wells which were drilled in 1987 and 1995 respectively in their own sedimentary part. With five deep boreholes at Soultz-sous-Forêts closely-spaced of about 500 meters (EPS-1, GPK-1, GPK-2, GPK-3 and GPK-4), there are many geological and geophysical data available for the Soultz-sous-Forêts site. EPS-1 borehole is an old oil well deepened and fully cored from 930 to 2227 meters (mainly in the lower Triassic) to characterize the granite reservoir, and used as an observation well for geothermal exploration (Dezayes et al. 2005). The four other wells (GPK-1 to 4) were drilled for power production (Gérard et al. 2006). All of these old wells were poorly investigated in their sedimentary part. In fact, to date, there are no precise geological and stratigraphic logs with the sedimentary formations encountered in Soultz-sous-Forêts because the primary objective was to characterize the deep fractured Paleozoic crystalline basement (Genter et al. 2015). Only the deep Permo-Triassic clastic sandstone overlying the basement by reason of a continuous core analysis was examined, the cover/basement interface

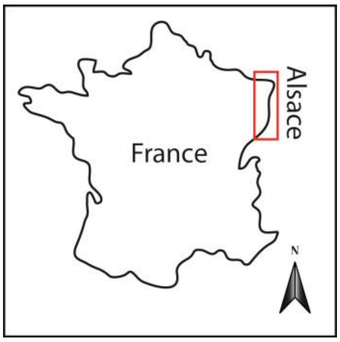

Figure 1*: Alsace region is located in north-eastern France.*

being part of the heat reservoir. The sedimentary cover/basement interface is the overarching goal for geothermal exploration because the heat circulates through it via a vertical fracture network permitting hydrothermal convective cells (Pribnow et Schellschmidt 2000). Before the GRT-1 litho-stratigraphic results (Aichholzer et al. 2015), there was no precise stratigraphic log (except the regional geological maps after Ménillet et al. 2015) in the area of the complete sedimentary cover. A detailed stratigraphic analysis, which has been calibrated on recently acquired knowledge at Rittershoffen (based on cuttings information and radioactive logs such as Gamma Ray: GR), will be proposed for the twenty-nine-year-old geothermal wells of Soultz-sous-Forêts. In addition to the stratigraphic contribution, a structural analysis of the main fracture zones intersecting the sedimentary part of the Soultz-sous-Forêts wells will be proposed.

2. GEOLOGICAL SETTING

Alsace region became a remarkable site for deep geothermal projects because of its high thermal gradient (up to 100°C/km in the uppermost part of the sedimentary cover) and by the presence of natural brines (in the order of 100 g/L) transporting heat to the earth's surface (Housse 1984; Schellschmidt et Schultz 1991; Le Carlier et al. 1992; Vernoux et al. 1995). As granite is a natural radioactive rock, heat production is enhanced by radionuclides' disintegration and the abundant fluids circulating through the fractured granitic basement transporting that heat. All of these reasons explain the twenty-nine-year-old Soultz-sous-Forêts' geothermal pilot project (1987) and the rise of a lot of new recent geothermal projects in Alsace (Genter et al. 2015). At Rittershoffen, the deep Paleozoic granitic basement is reached at 2200 meters depth instead of 1400 meters at Soultz-sous-Forêts, spaced about 6.5 kilometers from each other. These two geothermal sites have a similar litho-chronostratigraphic column including, from the base upwards, a granitic basement covered by a reduced Permian clastic formation, the whole Triassic sequence (Buntsandstein, Muschelkalk and Keuper), a reduced Jurassic units (Lias and lowermost Dogger, Malm being eroded, and Cretaceous never being deposited because of the major uplift of the region during the early rift phase from the upper Jurassic) and part of Eocene, lower Oligocene and Pliocene (Duringer 1995). A major erosional unconformity separates the Mesozoic from the Tertiary units which are constituted exclusively of Eocene (Paleocene was never identified), Lower Oligocene and part of Pliocene sedimentary rocks (Sittler 1969b; Duringer 1988; Schuler 1990; Sissingh 2003; Ménillet et al. 2015). These Tertiary layers are related to the opening of the graben from the middle Eocene. In this geographical area (Soultz-sous-Forêts and Rittershoffen), because of erosion, Upper Oligocene and Miocene do not exist. The uppermost part of the sedimentary cover is a loessian-clayey unit dated from the Pleistocene (Ménillet et al. 2015). The interpreted environmental deposits of this stratigraphic column (Aichholzer et al. 2015) are the following: the Pliocene-Quaternary period is characterized by loess deposits during Quaternary and fluvial, marshy and lake deposits during Pliocene. Oligocene is characterized by marine deposits in its upper part (*Série Grise*) and lacustrine to evaporitic in its lower part (*Couches de Pechelbronn*). Eocene is fully lacustrine and/or evaporitic according to the position in the rift. Close to the border (not represented on the log), marly facies from the basin became rapidly conglomeratic (fan-delta from rift borders) (Duringer 1988; Duringer et Gall 1994; Duringer 1995). Jurassic is a fully marine deposit. From top to base in the sequence, Triassic is characterized by lagoon environments (Keuper), marine to lagoon environments (Muschelkalk) and fluvial (lower Buntsandstein) to fluvio-deltaic deposits for the upper part of the Buntsandstein (*Grès à Voltzia*). Some parts of the Buntsandstein (especially the *Grès Vosgien supérieur*) display aeolian deposits. Permian is the oldest sedimentary unit in the graben covering the basement. It is characterized by fully continental deposits (from debris cones to fluvial environments).

3. METHODS

This new interpretation's work was made possible thanks to the results of geological analyses obtained during and after the drilling phase at Rittershoffen. It will enhance the basement/cover knowledge, and determine the precise chrono-lithostratigraphic units crossed by the GPK-1 and GPK-2 wells. In fact, GPK-2, GPK-3 and GPK-4 being close to each other, this paper will only present the results of GPK-1 and GPK-2 spaced of about 500 meters (GPK-3 and GPK-4 are quite similar to GPK-2). The main goal of this work is to determine the accurate depth of top and base of each formation and to highlight their thickness variations between Rittershoffen (GRT-1) and Soultz-sous-Forêts (GPK-1, GPK-2). The workflow process was a critical rereading and interpretation of the old masterlog with the analysis of the cuttings descriptions and calcimetry log. The masterlog is the report synthesizing the rock succession from top to base of the well (e.g. cuttings' description, calcimetry log, layers' interpretation, rate of penetration (ROP) of the drill bit during the drilling, date and depth, and occurrence of faults). The cuttings analysis is essential to get the description of the units crossed. Calcimetry log, especially the calcite/dolomite ratio may be essential for some formation identification. The occurrence of gypsum/anhydrite is another important tool for determining the units' limits especially in Tertiary, Keuper and Middle Muschelkalk. Combining the previous results with natural outcrops from Northern Alsace was an essential tool for the determination of the formation's boundaries in GRT wells used there as a reference well for the chrono-lithostratigraphic vertical succession (Aichholzer et al. 2015). Next step in the workflow process, for calibration, is the study of outcrops associated to the masterlog's results and existing cores, especially from the EPS-1 well. Cores from the EPS-1 well were only available for the Buntsandstein and the lower and middle part of the Muschelkalk but they permitted to increase the accuracy of the results. Finally the Gamma Ray log (GR) will be used to confirm or adjust the limits because it has the highest resolution. It constitutes therefore one of the best geophysical signatures for wells comparison especially if the descriptions of the series using the cuttings are not sufficient. The GR log is obtained by measuring the natural radioactivity produced by the adjacent rocks to the well, during the rise of the tool. Emissions of gamma electromagnetic waves come from the isotopes natural radioactive decay such as potassium (K), uranium (U) and thorium (Th) (AGR Pioneering Achievements 2013). The vertical resolution of the GR tool is of the order of 15 centimeters (6 inches) (Serra et Serra 2000), the unit being gAPI (giga American Petroleum Institute). Fifteen centimeters resolution means that small banks can be identified, which is particularly important for the Lias part, where many formation boundaries within this great clayey/marly unit are characterized only by such bank.

4. RESULTS

4.1 Visual methods for the stratigraphic correlations

First of all, the lecture of the log is along the vertical profile (right of the log) because it is representing a 1D well (fig. 2). The fracture zones (potentially faults) have been represented on the log with their observed apparent vertical displacement (fig. 2). These zones were observed because of a change in the stratigraphic succession (units entirely or partially absent or characterized with less thickness than expected). For the layers' thickness, the correlations are made each time on the right side of the log, represented with the help of a color scale. As the Gamma Ray is measured on the total length of the wells, all the limits are given in Measured Depth (MD) and not in True Vertical Depth (TVD) which correspond respectively to the length of the tube/drilling and the true thickness of the sedimentary units (representing the vertical depth at the drilling entry point). As the deviation of the well is low (25 meters horizontally at the deepest part at the top of the granitic basement), the thickness in MD is almost the thickness in TVD. To conclude, the logs only show the sedimentary columns. The final depth in the basement of each well is not drawn because this paper is focused on the sedimentary units. The log present in this abstract shows only the major limits, the detail of all the limits is in Aichholzer et al., (2016, submitted). The last point to mention is that the Gamma Ray was measured through the casing in GPK-2 from the surface up to 577 meters deep. After that limit, the GR log was obtained in open hole section. The casing impacts the resulting log because it mitigates the GR values measured but the general shape of the signal has not changed drastically. For GPK-1, the log was obtained in open hole section.

4.2 Chrono-lithostratigraphic sequence of Soultz-sous-Forêts (GPK-1 and GPK-2)

4.2.1 Pliocene-Quaternary

The sedimentary sequence begins with a thin sandy-clayey complex (10 meters for GPK-1 and 20 m for GPK-2), corresponding to the *Complexe du Plio-Quaternaire*. This uppermost unit is badly documented. For Soultz-sous-Forêts, the old interpretation in the masterlog does not give any information about these two units.

4.2.2 Oligocene (Rupelian)

This uppermost *Complexe du Plio-Quaternaire* lays with an erosional surface on Oligocene (early Rupelian) constituted by the *Couches de Pechelbronn supérieures et moyennes*. These later are two homogenous and monotonous units composed of calcareous clays intercalated by thin sandstone beds. The limit between middle and upper *Couches de Pechelbronn* is constituted by the *Zone Détritique de Glaswinkel*. This small unit consists in a massive sandstone layer which marks the base of the *Couches de Pechelbronn supérieures*. It is clearly observed on the cuttings description by the occurrence of sandstone cuttings but also on the GR log (fig. 2) with a sharp peak directed to the left (sudden increase of the ratio "sand/clay") compared to above and below it.

4.2.3 Eocene

a. Lower Priabonian to Bartonian

The Eocene is divided from top to base in three formations: the *Couches de Pechelbronn inférieures*, the *Couche Rouge* and the *Zone Dolomitique*. The limit between the middle and the lower *Couches de Pechelbronn* is difficult to determine. The transition from the *Couches de Pechelbronn* to the *Couche Rouge* is marked by a sudden increase of characterized red clays and a decrease of the carbonates content observed on the calcimetry log. After this massive red

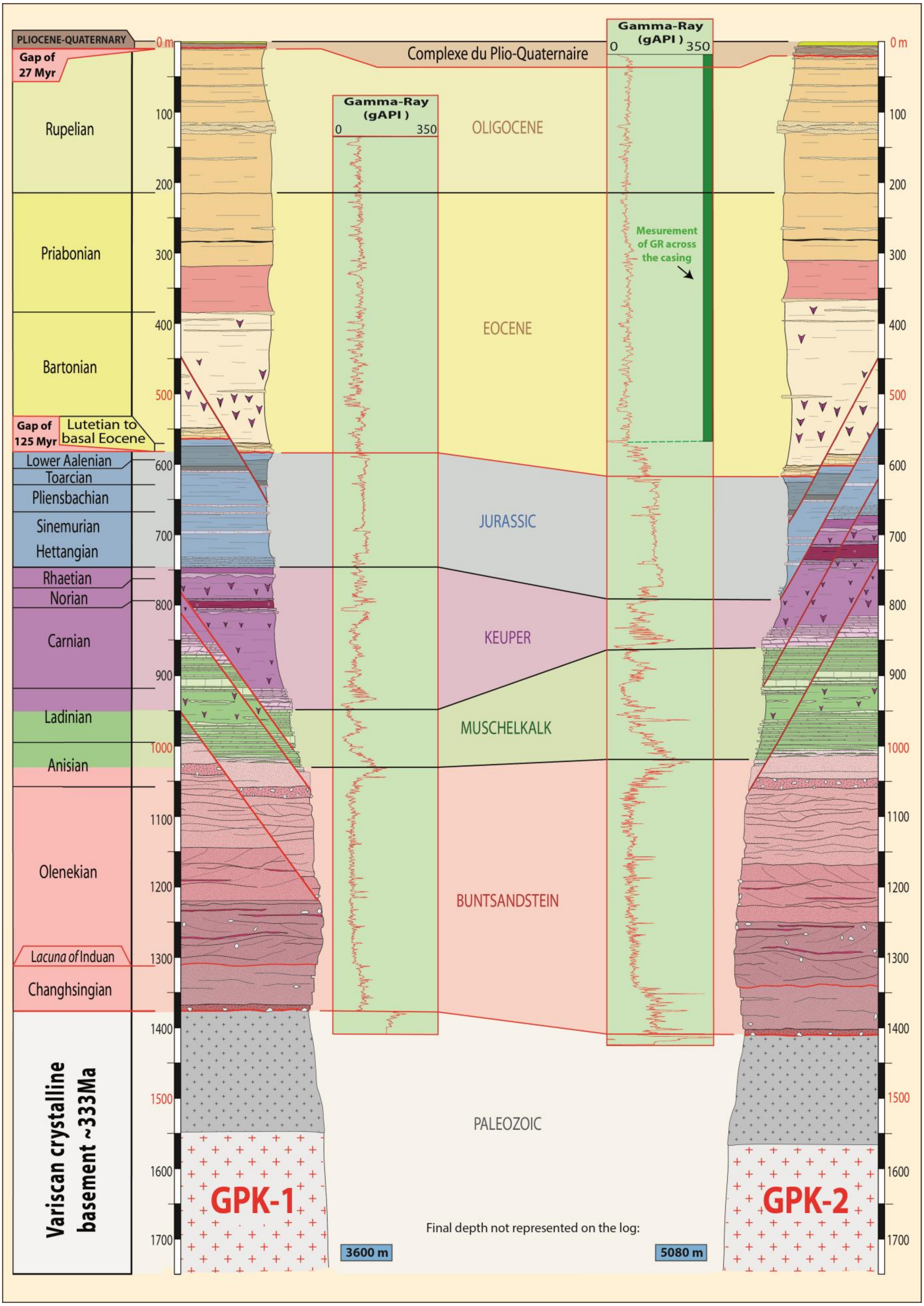

Figure 2: *Chrono-lithostratigraphic logs of the wells GPK-1 and GPK-2 (Soultz-sous-Forêts) with their GR log.*

clay unit (65 meters), the gradual increase of salt signs definitively the entrance in the *Zone Dolomitique*. The salt and these thin sandstone beds are observed on the GR log, because it induces important leftwards deviation of the signal.

b. Lutetian to basal Eocene

The *Zone de Transition* marks the limit between Cenozoic and Mesozoic. It is very difficult to define objectively its limits of top and base because of the huge lateral facies and thickness variations. Facies heterogeneity could be one of the best terms to define this formation. From few meters to ten, from clays to laterites, sandstones or limestones, conglomerates to breccias, it is often very complicated to give its precise position from cuttings examination only. The first best criterion is the disappearance of saline series characteristic from base of the *Zone Dolomitique*. Secondly, the arrival of lacustrine carbonates, sometimes in very massive habitus is another good criterion. Lastly, the occurrence of reworked Jurassic elements signs definitively the entrance in the *Zone de Transition* even if this reworked material makes it difficult to determine the limit with Jurassic. Concerning the Gamma Ray signal, it passes from large amplitudes related to the presence of sulfates (*Zone Dolomitique)* to a more sluggish signal (*Zone de Transition)*.

4.2.4 Jurassic (Aalenian to Hettangian)

The complete Jurassic sedimentary column is around 260 m thick. It is constituted mainly by monotonous grey or blue grey marls. Finding the formations' boundaries is largely based on the research of thin limestone beds positioned often on the base of formation. Jurassic starts at the lower Dogger with the *Formation de Gundershoffen* and the *Formation de Printzheim* (Toarcian) composed mainly of clays and silty clays. As the name suggests, the *Marnes de Schillersdorf* (Toarcian) are composed of black micaceous and silty clays, and argillaceous limestones interbedded with calcareous nodules. The identification of the *Couches à Posidonomya* called also *Schistes Carton* is based on the very fine laminated appearance and the organic-rich matter content. The *Calcaire de Kirrwiller* (Pliensbachian) is a twenty centimeter thick limestone bank, well identified at the entrance of the *Marnes à Septaria* unit thanks to the well-marked Gamma Ray (signal strongly directed to the left), which may be one of the most striking negative signals in the Lias. The *Marnes à Septaria* because of its marls is much more radioactive than the limestone, therefore the signal moves directly rightwards after it. This unit and the *Marnes à Ovoïdes* are composed of blackish calcareous silty clays. A huge fracture zone (potentially a fault), presents in both wells spaced of 493 meters, affects the *Marnes à Ovoïdes*. The thickness of this unit at Soultz-sous Forêts is therefore thinner than regionally. The *Calcaire de Zinswiller*, which gives another significant GR signal strongly directed to the left, is a limestone bank which makes the transition with the *Argiles de Bossendorf*, light gray colored clays where fossils are frequent in the field. As before, the *Calcaire de Gundershoffen* (Sinemurian/Hettangian) is a limestone bank making the transition with the unit underneath the *Formation d'Obermodern* composed of laminated calcareous clays, sandy to fine sandy, micaceous and pyritic. The *Calcaire de Rittershoffen* is the last well developed limestone bank in Jurassic. Already observed but not described in the Oberroedern well in 1987 (OBR-101), this massive limestone is a multi-metric bank (of the order of 5 meters instead of 0.20 m to 1 m for the others limestones benchmarks of the Lias). The GR signal, strongly directed to the left is unquestionably the most striking signal in the Jurassic sedimentary column. Moreover, this Jurassic massive limestone is clearly defined as hard rocks on the acoustic borehole log as well as on the caliper log showing a well shape close to the nominal borehole diameter. Underneath comes the *Formation de Hochfelden*, a silty and marly to calcareous clay unit. The *Calcaires et Marnes à Gryphées* just below is easily recognizable from the formation above because of its facies made of monotonous and regularly spaced decimeter limestones/marls alternations. It gives a specific GR signature at the base of the Lias, with huge amplitudes and short frequencies and the entire signal is less radioactive than the other unit of Jurassic (more leftwards).

4.2.5 Triassic

a. Keuper (Rhaetian to Upper Ladinian)

Keuper is formed of six formations, present entirely in GPK-1 but affected by fracture zones in GPK-2 (fig. 2). Compared to Jurassic, Keuper's facies are red and green colored and often with anhydrites occurrence. It contrasts sharply with the grey-dominated color of Jurassic and gives a huge criterion for the limits. It starts with the *Argiles de Levallois* composed of red to black silty clays covering the *Grès du Rhétien*, a sandstone formation, locally conglomeratic and well observed on the GR because the signal makes a strong peak directed leftwards. Then, below, the *Marnes Irisées supérieures* are composed mainly of clays, calcareous clays, argillaceous marls and dolomitic clays interbedded with dolomite banks. The *Argiles de Chanville* unit is composed of red clays, slightly micaceous and finely dolomitic. Moreover the cuttings description, the GR log shows a huge shift to the right (radioactive) because of the presence of these clays. The presence of the *Dolomie en Dalles* is not proved. After Ménillet et al. (2015), this unit is replaced in this area by a massive gypsum unit giving the huge GR signal directed to the left. The *Marnes Irisées moyennes* are colored marls similar to the marls of the *Marnes Irisées supérieures*. Just under, the *Grès à Roseaux* is undoubtedly the best benchmark in the Keuper. It characterizes a short fluviatile phase inside the huge argillaceous middle Keuper. The *Marnes Irisées inférieures* are composed of clays, locally calcareous and dolomitic with an abundant presence of gypsum/anhydrites. The lower Keuper called Lettenkohle is made from top to base of three units: the *Dolomie Limite;* the *Argile de la Lettenkhole;* and the *Dolomie Inférieure*. The *Dolomie Limite* (several decimeters), badly developed, is composed of shelly dolomitic banks. The transition is really visible between the two units because the *Dolomie Limite* compared to the *Marnes Irisées inférieures* with its dolomitic bank has a very weak GR signal (to the left) because it is not radioactive at all. The *Argile de la Lettenkhole* with its clays has a very strong positive signal (to the right of the GR log). This last unit is made of marls and dolomites alternations, with some decimetric sandstone banks close to the base. Therefore the GR signal increases again rightwards to the radioactive side. The *Dolomie Inférieure* is a very massive and compact dolomitic unit, again less radioactive (strongly directed to the left). The amplitude of the GR signal for the *Argile de la Lettenkohle* and the *Dolomie Inférieure* is the most important in the entire sedimentary column.

b. Muschelkalk (Lower Ladinian to Upper Anisian)

The Muschelkalk begins with the *Calcaire à Térébratules*, a formation composed of two massive limestone banks (up to 3 meters thick) slightly dolomitic. Below, the *Couches à Cératites* are made of a homogenous and monotonous unit alternating limestones and marls. For the *Couches à Cératites*, from top to base, the GR signal slowly increases rightwards before decreasing again leftwards up to the *Calcaire à Entroques* just below. This “go and back” is characteristic of this formation (deepening and shallowing of facies). Below, the *Calcaire à Entroques*, which is the most highly massive limestone without marls from the sedimentary column. It covers, the *Dolomie à Lingules*, a formation of dolomitic limestones and dolomitic marls. The *Marnes Bariolées* is characterized by sandy clays, red to gray, locally dolomitic, and of dolomitic marls with large amounts of anhydrites. The complex formed by the three formations grouped together: *Dolomies*, *Calcaires Ondulés*, *Couches à Myacites* are made of an alternation of marls, marly dolomites and dolomites. Finally, the last Muschelkalk unit is the *Grès Coquillier*, a shelly and dolomitic sandstone interbedded with clayey marl beds. As showed on the figure 2, the wells are affected by fracture zones in the Muschelkalk.

c. Buntsandstein (Lower Anisian to Changhsingian)

The Buntsandstein forms the base of the Triassic sequence. It is composed of seven red-dominated colored sandstone units. From top to base of the well the *Grès à Voltzia* formation is the first light red micaceous sandstone formation, so the transition to the Buntsandstein is easily recognizable with the change of color and the massive arrival of quartz. The second very good criterion is the presence of the biggest rightwards peak of the GR of the entire sedimentary column. This big GR signal is quiet similar in all the wells and marks the entrance in the Buntsandstein. After this very fine-grained argillaceous sandstone comes the *Couches Intermédiaires* with a coarser-grained texture and a color progressively changing from light red to red. The clay percentage decreases progressively down to the formation, giving a GR signal decreasing quickly again to the left too, from top to base. The EPS-1 cores analysis in the Buntsandstein permitted to increase the recognition of the limits in the *Grès Vosgien*. It is composed of the *Couches de Karlstal* (poorly cemented aeolian facies), the *Couches de Rehberg* and the *Couches de Trifels* both fluviatile. These pink to red-brown sandstone formations are quite identical to another one and the proportion of feldspar is basically the same from top to base of these units. The GR log does not give any particular signal, except between the *Couches de Rehberg* and *Couches de Trifels* characterized by three well developed (up to 20 cm thick) red clays, therefore observed on both of the GR log by three peaks directed to the right and on the cores of EPS-1. The *Grès d’Annweiler* and the *Permien anté-Annweiler* are both units from Upper Permian but named as the *Buntsandstein Inférieur*. Besides its GR signature that is characteristic with a more radioactive signal than the *Grès Vosgien* because they are more clayey, a distinctive color change is observed. In many characteristics, (GR signature and fine-grained sandstone) these Permian units are quite similar to the *Grès à Voltzia* unit. Indeed these Permian sandstones are darker, from dark red to reddish brown. Both wells (GPK-1 and GPK-2) show the presence of fracture zones at the *Couches*

Intermédiaires transition with the *Couches de Karlstal* and in GPK-1 another is present in the *Couches de Trifels* (fig. 2).

4.2.6 Paleozoic granitic basement

The granitic basement appears at first glance at the GR log. In fact, when the signal is continuously directed to the right side of the log, it means that the unit is very radioactive, and the most radioactive formation is the granitic basement. The sedimentary cover may have radioactive minerals but not as strong as granite. Therefore the huge movement to the right is associated to the entrance of the tool in the Paleozoic basement at 1375.5 meters for GPK-1 and 1411.5 meters for GPK-2 respectively.

4.3.1 Fracture zones and associated units reduction

Several major fracture zones are present in both of the Soultz-sous-Forêts' wells (GPK-1 and GPK-2). Two of them are affecting the *Marnes à Ovoïdes* (Jurassic) in GPK-1 and GPK-2, lacking two-thirds of it thickness. For the other Jurassic units, the thickness is approximately the same, the few variations being caused only by weak lateral thickness variations. The presence of six other fracture zones (potentially faults) was observed, affecting the Muschelkalk and the Buntsandstein units in GPK-1, and affecting the Keuper, the Muschelkalk and the Buntsandstein in GPK-2. GPK-1 has not the entire sequence of the Middle Muschelkalk, reduced about one-third. In fact, the forty-meters of *Marnes Bariolées* are entirely missing and the base of the *Dolomie à Lingules* is also affected. For the Buntsandstein it is the *Couches Intermédiaires* (one half missing) which is affected and the *Couches de Rehberg*. For GPK-2, in the Keuper, twice of this formation is lacking because the *Argiles de Levallois – Grès du Rhétien*, the *Marnes Irisées supérieures*, the *Argiles de Chanville* and the *Dolomie Limite – Argile de la Lettenkhole – Dolomie Inférieure* are absent. For the Upper Muschelkalk formation, it lacks 5 meters of the *Calcaire à Entroques* which is half of the unit. In the Buntsandstein, the fault makes the *Poudingue de Saint-Odile* disappear and affects the top of the *Couches Intermédiaires*, lacking 27 meters. In both wells, for all the other units of the sedimentary sequence, the thicknesses are almost the same. The little variations represent the lateral variations of these units. If we sum, the thickness of the units affected by faults reduces the sedimentary column of 161.5 m for GPK-1 and of 191.5 m for GPK-2 respectively. Knowing that the basement is at 1375.5 m for GPK-1 and 1411.5 m for GPK-2 and 2198 m for GRT-1 (Rittershoffen), we know that 822.5 m are missing in GPK-1 and 786.5 m in GPK-2. The thickness reduction by erosion (642.5 m) and faults (161.5 m) is 804 m (GPK-1) which means that 18.5 m are explained by little lateral variations of units. For GPK-2, 795.5 m are lacking in the sedimentary column. Without the thickening of 12.5 m (*Calcaire à Térébratules – Couches à Cératites*), the reduction is 783 m (erosion: 604 m, faults: 191.5) which means 3.5 m of lateral thickness variations.

5. FRACTURES ZONES IN GPK-1 AND GPK-2

In this paper we define well logs (GR, caliper, density, porosity) and instantaneous well logging data as mud logging (gas anomalies, rate of penetration of the tool ROP, mud losses). Caliper is the log which measures the internal diameter of the borehole. If there is any fracture zone, the diameter of the unit will not be circular anymore but could be enlarged and therefore we could identify an anomaly in the caliper. An anomaly in temperature means that at one precise depth there is a higher or a lower temperature than in the surroundings. The natural gas emission is monitored during the drilling phase. The log obtained indicates which formations have gas emission (alkanes, CO_2…) and which depth we observe anomalies compared to ambient background. If there is any loss of the whole drilling fluid (mud) at any depth to the formation, it means that there is a permeable fracture zone. Other geophysical measurements are the bulk density of the rock formation (recorded in g/cm^3) and the neutron porosity (measured in percent). The term log cuttings will include macroscopic descriptions (cuttings, cores), field observations and GR well log. And it is with the log cuttings that this chrono-lithostratigraphic analysis was done. The mud logging has been used to compare the stratigraphic results to a structural analysis. In term of fault, we consider that if there is any significant thickness variation from a given layer, it can be the sign of the occurrence of a normal fault. With mud logging, more arguments were given for the presence of faults observed in the stratigraphic analysis. Based on mud losses mainly, we can define the permeability of a given structure (faults, fracture zones).

5.1 GPK-1 fractures analysis

From the stratigraphic analysis, it is observed that the *Marnes à Ovoïdes* are reduced in comparison with Rittershoffen (19 m instead of the 44 m expected). On mud logging, millimeter opened fractures with oil (also observed on cores) at around 635 m depth are observed. Deeper in the well, in the Muschelkalk formation, the *Marnes Bariolées* are absent of the sedimentary sequence. Moreover, the top of the complex constituted by the *Dolomies – Calcaires Ondulés – Couches à Myacites* and the base of the *Dolomie à Lingules* is affected. And on the mud logging, millimeter to centimeter fractures filled with calcite, quartz, oil and bitumen were observed. Anomalies in caliper, temperature, neutron porosity and ROP, decrease of density and increase of porosity were also observed at that depth. The *Couches Intermédiaires* are reduced about 29.5m in comparison with Rittershoffen. Issued from the mud logging, between 1042-1049 m depth, several caliper anomalies, variations in neutron porosity, temperature and bulk density were observed. Therefore it is confirmed that we have a fault affecting this unit. The *Couches de Rehberg* is twice reduced in comparison with Rittershoffen (33 m instead of 79.5 m). On the cores, anhydrites filling were observed. From mud logging, anomalies in temperature and ROP, and between 1219 and 1240 m total mud losses which involves a permeable fault at 1219 m was observed. Those two faults in the Buntsandstein are interpreted as branches of the Soultz-sous-Forêts Fault, going from the surface down into the granitic basement with approximately a 100 m cumulated vertical fault offset (Koelbel et al. 2011).

5.2 GPK-2 fractures analysis

From the stratigraphic analysis, it is known that the *Marnes à Ovoïdes* is reduced in this well too, in comparison with Rittershoffen (22.5 m instead of the 44 m expected). On mud logging, gas anomalies were observed around 675 m. For the Keuper, most of the units are missing: *Argiles de Levallois – Grès du Rhétien – Marnes Irisées supérieures – Argiles de Chanville – Dolomie en Dalles – Marnes Irisées inférieures – Grès à Roseaux*. On mud logging, at 793 m depth, a positive ROP anomaly and a decrease in gas log were observed. One half of the *Calcaire à Entroques* is absent (5 m instead of the 10 m expected) and the mud logging shows big caliper and gas anomalies and mud losses which involves permeability. Lastly, the *Poudingue de Sainte-Odile* is absent and the top of the *Couches de Karlstal* is affected. On mud logging, caliper and gas anomalies were observed.

6. CONCLUSIONS

Issued from the geothermal doublet (GRT-1 and GRT-2) at Rittershoffen, the drill cuttings analyses combined with a geological calibration on regional outcrops provided a very detailed and complete chrono-lithostratigraphic log. Therefore, the Rittershoffen's logs have been used as a baseline in order to reinterpret the sedimentary succession from GPK-1 and GPK-2, boreholes from Soultz-sous-Forêts, which were poorly investigated in the past. This geological studies issued from surveys logs, field work, geophysical data and cores/cuttings from the geothermal wells at Soultz-sous-Forêts and Rittershoffen provided both a chrono-lithostratigraphic log of the historical Soultz-sous-Forêts wells and lateral well-to-well comparisons between the old (Soultz-sous-Forêts, 1987) and recent (Rittershoffen, 2012-2015) geothermal wells. One of the first results at Soultz-sous-Forêts compared to Rittershoffen is the substantial reduction by erosion of Tertiary and Quaternary formations. It lacks the whole *Série Grise* and the upper part of the *Couches de Pechelbronn* (Oligocene) and almost the entire *Complexe du Plio-Quaternaire* formations, which all represent a cumulated thickness of about 444 meters. A second difference is located at the Mesozoic/Cenozoic unconformity. The erosion on the upper part of the Jurassic is more marked in the Soultz's sedimentary column and therefore several units of the Dogger are absent, removed during the Cretaceous/early Tertiary emersion. Compared to Rittershoffen, it lacks around 35 m of the upper Jurassic formations in the Soultz's wells (*Argiles Sableuses* and *Formation de Schalkendorf*). The occurrence of two normal faults which are affecting the Lias and the Muschelkalk units in GPK-1 borehole were highlighted. The fault observed in the Lias (641 m) led to the disappearance of the major part of the *Marnes à Ovoïdes* formation. The fault observed in the Muschelkalk (1002 m) makes the complete *Marnes Bariolées* and the lower part of the *Dolomie à Lingules* formations disappear. Lastly, in GPK-1, two faults were observed in the Buntsandstein (1049 and 1219 m), one affecting the base of the *Couches Intermédiaires* and the top of the *Poudingue de Sainte-Odile* and the second one affecting the *Couches de Rehberg*. In GPK-2, we highlighted four normal faults, also in the Lias (686 m), one in the Muschelkalk (911 m) and one in the Buntsandstein (1064 m) but in the Keuper too (793 m). If we sum what is lacking in the stratigraphic column of Soultz-sous-Forêts, compared to the one of Rittershoffen, it is reduced of around 790 m. In GPK-1, the three deepest faults (1002 m, 1049 m and 1219 m) could correspond to the imbrication of the Soultz-sous-Forêts fault branches as it is observed on the seismic profile (Koelbel et al. 2011). In GPK-2, the three deepest faults (793 m, 911 m and 1064 m) could also be the Soultz-sous-Forêts fault branches. In fact, due to the complex geometry of this fault, these branches are observed at shallower depth compared to GPK-1. The fault located at 641 meters depth in GPK-1 and 686 m in GPK-2 is affecting the same unit in both of the wells: the *Marnes à Ovoïdes*. The same apparent vertical offset is observed, because in each well two thirds of the unit are missing (respectively 19 and 22.5 meters instead of the 45 m expected at Rittershoffen). This means that it could be the same fault affecting this Jurassic unit at Soultz-sous-Forêts. Thus, the detailed lithostratigraphic units' analyses calibrated on the Rittershoffen's geothermal wells are a very powerful technique for improving the geological knowledge such as 2D seismic profile in this part of the Upper Rhine Graben, which is very interesting in terms of geothermal project development. Moreover, with this stratigraphic work, it has been possible to highlight some faults with important thickness variations. With a structural analysis, combining well data (mud logging) and seismic profile, those faults were precisely located in depth in each well. Therefore, this geological analyses contribute to seriously improve the knowledge of the sedimentary part of the deep geothermal wells and therefore secure the coming geothermal projects development. To go further in this 2D structural analysis, it could be very interesting to carry out a 3D geometric model considering the real trajectories of the wells and the actual 3D geometry of the faults.

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