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GEOTHERMAL POTENTIAL ASSESSMENT OF CLASTIC TRIASSIC RESERVOIRS (UPPER RHINE GRABEN, FRANCE)

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ABSTRACT

To develop the sustainable energy in France, a new geothermal exploration project has been launched in the Upper Rhine Graben for heat or electricity production. This resource is located in clastic formation of the lower Triassic unit, namely the Buntsandstein.

The goal of this study is to make a first assessment of this sedimentary reservoir at two different scales. In a first step, we used public available data (map, borehole data…) to assess the geothermal potential of the Buntsandstein at the Upper Rhine Graben scale in order to delineate the most favourable areas for future exploration and exploitation of the geothermal resource. It appears that the northern part of the Rhine graben constitutes a more favourable area than its southern part. The top of the reservoir located at around 2000m depth is characterized by a temperature of about 150°C and a sandstone thickness around 600m. Based on Muffler & Cataldi works (1978), the computation of the heat in place gives a geothermal potential between 15 and 30GJ/m^2.

In a second step, a 30km x 35km area located between Strasbourg and Obernai in France has been investigated. Based on a detailed geological study combining data derived from 13 previous oil boreholes and 143km length of seismic profiles, the main sedimentary interfaces including geological layers and faults have been interpreted between the outcropping Quaternary layers and the deeper parts made of Permo-Triassic formations. From that interpretation, 3D geological models have been yielded based on different hypotheses. These models, constructed with the Geomodeller software developed by BRGM, allow calculating the volume of modelled sedimentary formations. According to the modelling results, different reservoir volumes have been computed which impacts the estimation of the overall geothermal potential. Temperature conditions derived from BHT (Bottom Hole Temperature) data in boreholes reaching the Buntsandstein sandstones, show a high average geothermal gradient (between 50°C/km and 58°C/km), which tends to indicate a significant geothermal potential. In the investigated area, the volume of the Buntsandstein reservoir is about 300km^3 and the exploitable heat quantity is around 350GW.year ± 5%.

INTRODUCTION

In France, the geothermal heating production is mainly concentrated within the Paris Basin, where about 30 geothermal doublets have been exploiting the Dogger limestone reservoir since the 80's and produce about 4000 TJ.year with an installed capacity of about 240MWt (Laplaige et al., 2005). The development of renewable energy necessitates exploring new or poorly well-known deeper sedimentary geothermal reservoirs, located in other promising areas. Thus, in order to promote renewable energy in France, Ademe (French Agency for Environment and Energy Management) and BRGM (French Geological Survey) launched a new research project for a geothermal appraisal of the low to medium temperature resources embedded in clastic reservoirs mainly focused on sedimentary basins (Paris Basin, Rhine Graben, Limagne Graben; Genter et al., 2005). In this framework, we conducted a comprehensive study about the deep sedimentary geothermal potential of the Rhine graben for heat and/or electricity production. The geothermal resource belongs to the silico-clastic formations embedded within the thicker Triassic sediments made of argillaceaous sandstones, where temperatures are often higher than 100°C based on previous deep geothermal borehole data (Cronenbourg, Rittershoffen, Soultz; Munck et al., 1979).

The goal of this study is to make a first assessment of this reservoir at two different scales. In a first step, we used public available data (map, borehole data…) to assess the geothermal potential of the Buntsandstein at the Rhine Graben scale in order to delineate the most favourable areas for exploration and exploitation of the geothermal resource. In a second step, in order to assess a whole methodology for estimating the geothermal potential of the silico-clastic formations of the Rhine Graben, we studied the Buntsandstein reservoir of a limited area near Strasbourg based on borehole data and reflexion seismic profiles.

GEOLOGICAL AND GEOTHERMAL SETTING OF THE RHINE GRABEN

The Rhine Graben is a Cenozoic graben belonging to the west European rift system (Ziegler, 1990), which is very well-known because of numerous studies for petroleum and mining exploration (boreholes, geophysical surveys…).

It is located in the extreme NE part of France with its western part and in Germany for its eastern part. The graben is 30-40km large and 300km long and the Rhine river flows through it. (tu aurais pu mettre une petite carte simplifiée car les américains ne connaissent pas la géographie).

The Rhine Graben is a part of the Cenozoic peri-alpine rifts with a Tertiary and Quaternary filling with a rather discrete volcanic activity, which overlays the Jurassic and Triassic sediments and the Paleozoic crystalline basement.

This graben is formed by three segments limited by border faults oriented N15°E in the North and the South parts, and N30-35°E in the middle part (figure 1). Two crystalline massifs surround it with the Vosges massif on the western part and the Black Forest on the eastern part. Between these mountains and the Rhine valley are located fracture fields. They are bands of fractured terrains, which collapse progressively giving a general framework in stairs (figure 1). In the North, the rift valley is limited by the Hercynian fault of the Rhenish Shield and in the South, by the Jura front and the transfer Rhine/Saône fault. This fault permits to do the link with other Tertiary grabens, namely the Bresse and the Limagne grabens (Bergerat, 1980).

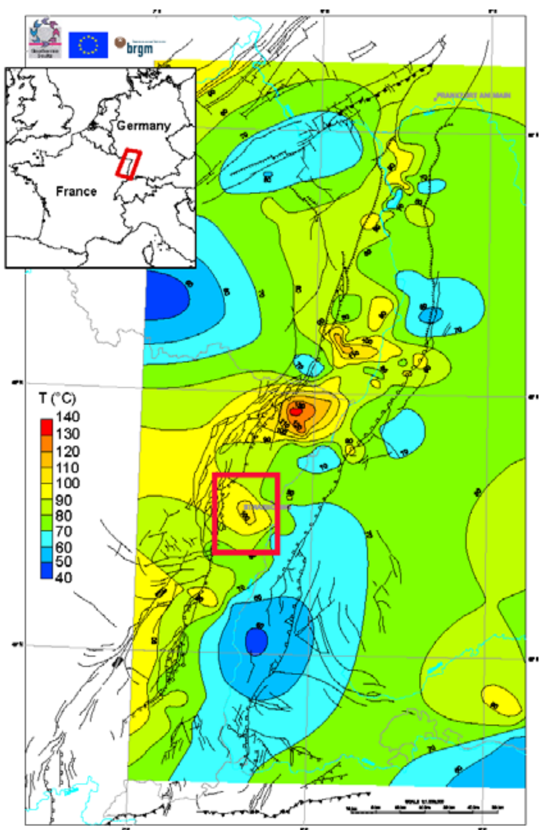

Figure 1 – Structural map of the Upper Rhine Graben and temperature distribution extrapolated at 1500m depth (GGA Hannover database in Genter at al., 2004). Red square: location of the local study.

Several major subsidence phases related to the Rhine graben tectonics generated variable sediment thicknesses. The subsidence starts at the end of Eocene (Lutetian) and continues during Oligocene with an E-W extensional regime. From the Upper Oligocene (Chattian), the subsidence is different between the northern and the southern parts of the graben, on both sides of the Erstein limit, which is the continuation of the regional Lalaye-Lubine-Baden-Baden hercynian fault (Villemin et al., 1986; Schumacher, 2002). In the southern part, the subsidence decreases and stops at the end of Oligocene (Chattian-Aquitanian). By the end of the subsidence, the graben borders raises inducing the uplift of the Vosges and the Black Forest massif. In the northern part of the graben, the subsidence is quite regular and homogenous until the Upper Miocene. The subsidence rate is less important and the graben borders are less uplifted (Villemin et al., 1986).

Due to the rifting, Moho uplifts implying a large-scale geothermal anomaly. Associated to that, small scale geothermal anomalies are due to fluid circulations within fracture zones (figure1; Pribnow and Schellschmidt, 2000). These local anomalies are mainly located along the Western border of the graben and the fluid circulates from East to West associated with the border faults (Benderitter and Elsass, 1995; Pribnow and Clauser, 2000). Inside the Rhine graben, several local geothermal anomalies occurred and are spatially distributed from the South to the North: Selestat, Strasbourg, Soultz (in superimposition with the petroleum field of Pechelbronn), Landau (also a petroleum field), Wattenheim (NE Worms) and Stockstadt (SW Darmstadt) (figure 1).

In this framework, we have studied the geothermal anomaly located close to Strasbourg, in the South-West part of the town (figure 1). In the French part of the Rhine graben, this anomaly constitutes the second anomaly in terms of thermal gradient, after those of Soultz.

GEOTHERMAL POTENTIAL ASSESSMENT AT THE RHINE GRABEN SCALE

Data available

In order to identify geothermal favourable area, we have yielded interpolation maps of main characteristics of the Buntsandstein aquifer such as depth, thickness, and temperature. This concerns the southern part of the Upper Rhine Graben including the both French and German parts

These maps were built from with existing database and compilation derived from the Geothermal Synthesis of the Upper Rhine Graben (Munck et al., 1979) published by the Commission of European Communities. The goal of this document was to make an inventory of natural geothermal resources of the Union members in 1975. In our approach, we did not

collect any new data but we used new sophisticated interpolation methods.
For our study, we used data of Buntsandstein formation such as depth of the top, depth of the bottom of the layer and the temperature. The digitalized data have been interpolated taking into account the presence of faults with a krigeage method with linear variogram without derive. We obtain grid map with 500m step, which allows computing the geothermal potential.

Analyses and results

The geothermal resource is defined as the part of accessible resource "that could reasonably be extract at costs competitive with other forms of energy at some specified future time" (Muffler & Cataldi, 1978). To quantify this resource, we calculate the quantity of heat, which could be extracted from a rock volume (1):

$Q = \rho \cdot C_p \cdot V \cdot (T_i - T_f)$ in Joule (1)

where ρ: rock density, C_p: heat capacity, V: volume of rock, T_i: initial temperature of the reservoir, T_f: final temperature after the total exploitation of the reservoir, or surface temperature and Q the heat extracted when the temperature decrease to T_i to T_f.
ρ and C_p are depending of the nature of the rock and could spatially vary. However, in this case, we take mean values for sandstone (Table 1).

Rock density	ρ	2200 kg/m^3
Rock heat capacity	C_p	710 J/kg.K
Rock volume	V	300 km^3
Initial temperature	T_i	90°C
Final temperature	T_f	10°C

Table 1 – Values of parameters for sandstone

This quantity of the thermal energy represents the geothermal resource base and not the power that can be generated. The size of the accessible resource is much smaller that implied by this simplistic analysis. Only a part of this resource is extracted and defined by a recovery factor, R, that depends on the extraction technology used (Muffler & Cataldi, 1978; Hurter & Schellschmidt, 2003). This recovery factor R is constituted by a "temperature factor" (R_T) and a "geometric factor" (R_G). In a doublet system, where there are a production borehole and an injection borehole, it can be shown that (Lavigne, 1978):

$R_T = (T_i - T_{inj}) / (T_i - T_f)$ (2)

where T_{inj} is the injection temperature. A group of experts of the European Commission recommended a value of 25°C for T_{inj} (Hurter & Schellschmidt, 2002).
The "geometric factor" is an empirical value (Lavigne, 1978). For an aquifer reservoir, the geometric factor is 0.33 (Hurter & Schellschmidt, 2002), then:

$R = 0.33 \cdot (T_i - T_{inj}) / (T_i - T_f)$ (3)

And then, the assessment of exploitable heat quantity is given by (4):

$Q_{expl.} = R \cdot Q$ (4)

The computation of the exploitable heat quantity per square meter from Basel to Karlsruhe shows that the area in the southern part of the Upper Rhine Graben is few favorable for geothermal exploitation (figure 2). On the other hand, the northern part shows more interesting values, with individual basins having high potential (Figure 2). In this northern part, the top of the Bundstandstein is at around 2000m depth with a temperature about 150°C and a thickness about 600m. The geothermal potential computed is between 15 and 30 GJ/m^2. In total, for the whole Upper Rhine Graben considered, the geothermal potential is about 330.10^{6}TJ for a 7150km^2 area from Basel to Karlsruhe.

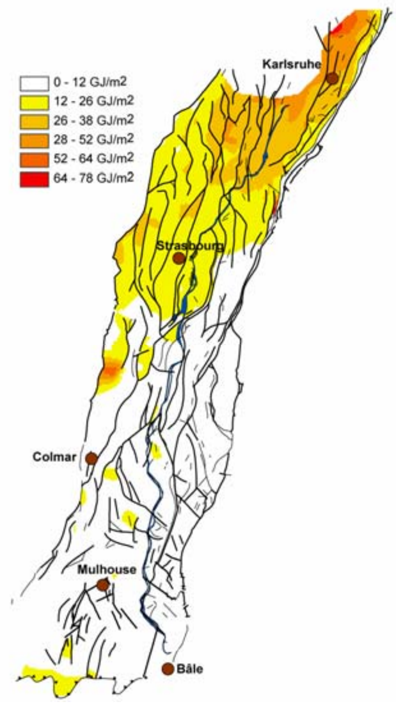

Figure 2 – Map of exploitable heat quantity per square meter for the Buntsandstein formation.

LOCAL STUDY OF A HIGH GEOTHERMAL POTENTIAL AREA

Location

The studied area corresponds to the anomaly located close to Strasbourg, in the South-West part of the town (figure 1). The dimension is about 30kmX35km and is located on the West border of the graben, near the Rhenane fault and at the South point of the Saverne fracture field (figure 1). At the graben scale, the temperature extrapolated at 1500m indicates 100°C that shows a thermal gradient of 66°C/km (figure 1).
In this zone, a detailed study has been done from borehole data and seismic profiles in order to outline the geometry of the clastic reservoir of the Buntsandstein sandstones and to determine its geothermal characteristics (temperature, flow, thickness, depths, …). From these data and the

petrophysical properties of this aquifer, an estimation of the geothermal potential of this limited area has been proposed.

Data available

Oil exploration was extensive in the Upper Rhine Graben. A lot of seismic profiles have been acquired in the framework of the petroleum exploration between the 70's and 80's. A selection of 143km of seismic reflection profiles in time, collecting data from previous surveys of 1975, 1985 and 1987, has been reprocessed (the velocity analysis have been improved) and reinterpreted in order to determine the geometry of the main interfaces of the geological formations embedded the geothermal sandstone reservoirs (figure 3). Five seismic cross sections are transverse to the graben structures and two others are oriented parallel to the graben axis that means they cross cut the first ones (figure 3). At the extreme southern part of the investigated area, the transverse seismic line 87ADL1, is not crossed by any of the longitudinal seismic lines, that will poorly constrain the geological interpretation.

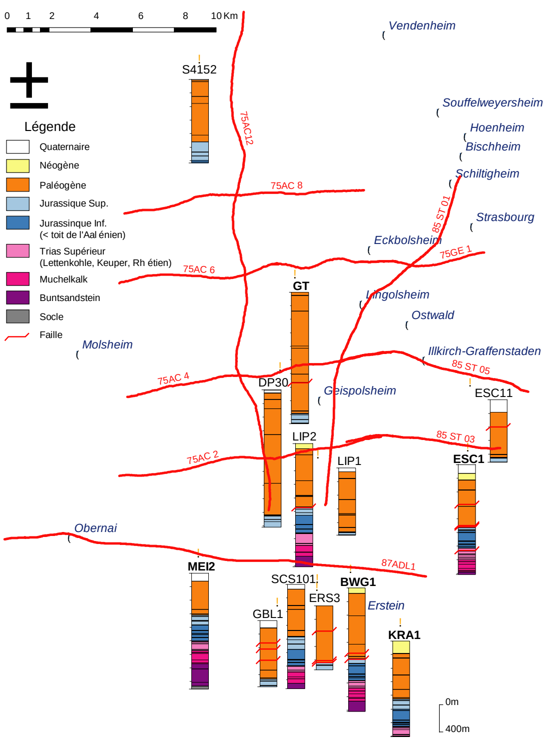

Figure 3 – Location of boreholes and seismic profiles, and geological logs in the boreholes. Boreholes with bold name have well velocity surveys.

In order to convert the time of the seismic interpretations in depth, we use the velocity fields measured in the boreholes to calibrate the seismic horizons of the seismic lines with the geological formations of the boreholes. Only five well velocity surveys exist but the borehole repartition is heterogeneous: four of them (MEI2, BWG1, KRA1, ESC1) reach the Triassic formations and give velocity field for the whole sedimentary cover. Unfortunately, they are concentrated in the southern and eastern boundary of the studied zone (figure 3). The other borehole (GT), located in the centre of the studied area, reaches only the top of Jurassic. The velocity field on the whole studied zone is poorly constrained considering the structural complexity of the studied zone. However, the seismic lines have been interpreted to determine the location of faults and the limits of main formations such as the top of Pechelbronn layers, the base of Tertiary, the top of Aalenian, the top of Trias, the top of Muschelkalk, the top of Buntsandstein and the top of crystalline basement (figure 4).

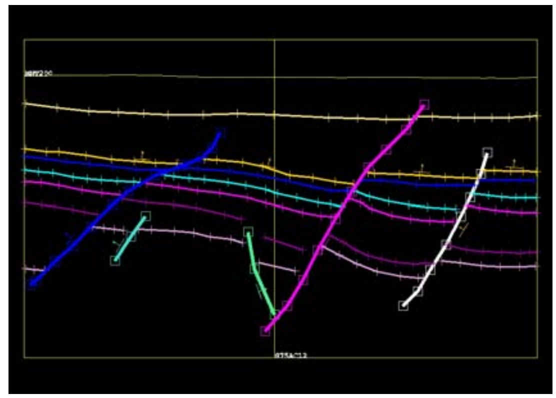

Figure 4 – Example of interpreted seismic cross-section (75AC6 profile).

Other boreholes complete the study (figure 3). They reach at least the Jurassic formations, where the Grande Oolithe is an aquifer reservoir, and 5 of them reach the Triassic sandstone (figure 3). The Meistratzheim-2 (MEI2) borehole reaches the crystalline basement and constitutes a good reference borehole for defining lithology.

As there are boreholes for petroleum exploration, only Bottom Hole Temperature (BHT) is available. These BTH data are measured in almost all industrial wells at the deepest part of the well immediately after the end of drilling phase and are then thermally disturbed by the mud circulation. The raw data have been corrected by statistical method (AAPG; Bodner et Sharp, 1988) or analytical method (ICS; Goutorbe et al., 2007). Then, these temperatures indicate a geothermal gradient ranging between 42°C/km and 66°C/km, with an average at 52°C/km (figure 5).

This geothermal gradient deduced from borehole data is twice those well known in the Paris Basin. The curve of the temperature vs depth shows regular evolution with depth and is not influenced by the lithology (figure 5).

The normal faults are NNE-SSW striking and dipping eastward or westward forming horst-graben and half-graben structures. Inside the faulted compartments, the sedimentary layers show tilted blocks with opposite tilting.

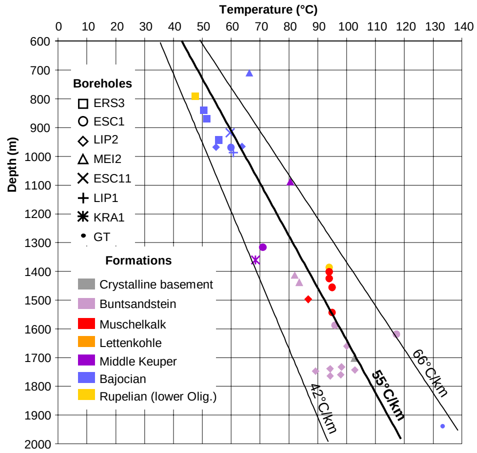

Figure 5 – Temperatures in the previous oil boreholes and calculated geothermal gradient. Location of boreholes: figure 3.

Thanks to the GeoModeller software developed by BRGM, a 3D model of the deep Triassic sandstone formation is outlined. The modeled area is a 30km on X-axis, 32km on Y-axis and 7km along the vertical. In this software, faults are explicitly represented by limited or unlimited surfaces whereas the stratigraphic interfaces are interpolated (figure 6), using potential field cokriging method (Lajaunie et al., 1997). In this method, one takes simultaneously into account interface locations, orientation data and fault influence.

In the northern part of the area, where the 6 seismic lines are intersecting each others forming a grid pattern, the fault correlations are well constrained, forming horst and graben structures or half-grabens. However, the southern cross-section, namely the 87ADL1 seismic profile, shows another fault pattern, with a large graben in the West part and a series of numerous dipping eastward faults in the eastern part.

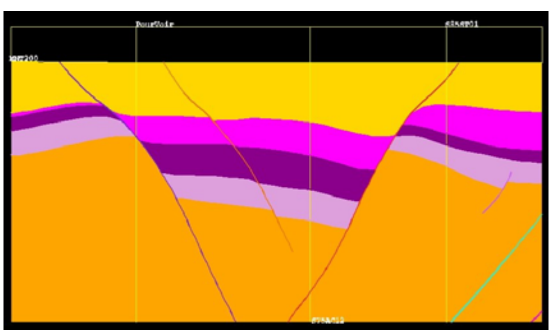

Figure 6 – Example of interpolated interfaces and faults in a seismic cross-section (75AC6 profile). Yellow: Tertiary, pink: Jurassic and lower Trias, purple: Muschelkalk, violet: Buntsandstein, orange: crystalline basement.

The difference between structural pattern in the northern part and in the southern part of our studied could be explained by the Southern Transfer Zone of the Rhine Graben. At the graben scale, this transfer zone subdivides the graben into a northern and a southern half-graben with opposite polarities and master fault shifts from the eastern to the western margin (Derer et al., 2005). This transfer zone is associated to the Variscan Lalaye-Lubine-Baden-Baden fault zone (Villemin et al., 1986; Schumacher, 2002).

As our studied zone is located in the vicinity of this transfer zone, the tectonic evolution appears complex. Fault trace correlation is then complicated by the presence of this transfer zone. Different configurations of linking fault traces are tested, according to their location, apparent slip throw and dip direction. We look at the effect of each configuration on interface interpolations. This leads as to retain hypothesis which leads to the minimum intra-block distortion in the interfaces. As an example, the configuration shown on figure 7 has been rejected and we favour hypothesis illustrated of figure 8.

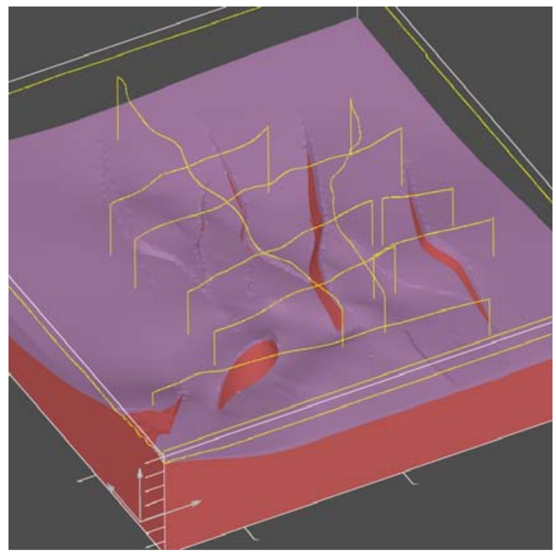

Figure 7 – View to the NE of a model, which is rejected because of intra-block distortion. Violet Buntsandstein reservoir, red: crystalline basement

This most probable geological model shows a fault network with NNE-SSW striking orientation (figure 8). In the southern part of the model, the basement is at around 2000m depth, whereas in the northern part, the basement ranges between 3400m and 4000m depth.

A huge fault crosses the model area and has a dip-slip throw higher than 1000m. This fault is associated in the SE part of the model with another huge fault with a throw of around 1000m, forming a graben structure with NE-SW striking orientation. In the deeper part of this graben, the basement is at 3800m depth (figure 8).

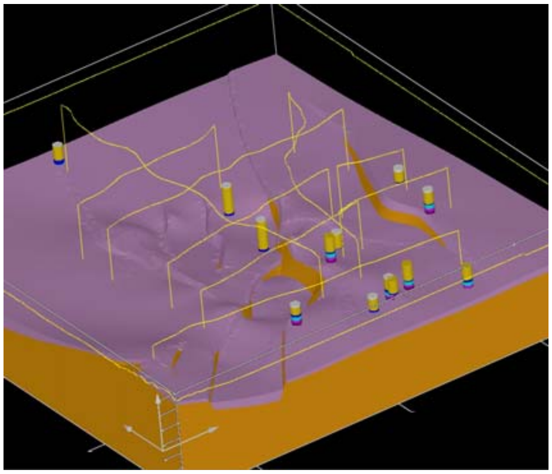

Figure 8 – View to the NE of the accepted model. Violet: Buntsandstein reservoir, orange: crystalline basement. The cylinders represent the boreholes.

Reservoir geometry and geothermal potential

Based on the accepted 3D model (figure 8), 2D thickness maps have been exported with a 200m grid resolution.

The map of the top of the Buntsandstein sandstones indicates a general deepening to the North (figure 9). In the northern part of the studied area, the top of the Buntsandstein ranges between 3200m and 3700m depth, and reaches 3880m depth at the base of the centre tilted block. In the southern part, the top of the Buntsandstein reaches 1000m to 1500m depth and 200-300m depth in the border of the Vosges massif. Between the faults, the major tilted blocks are dipped to the East.

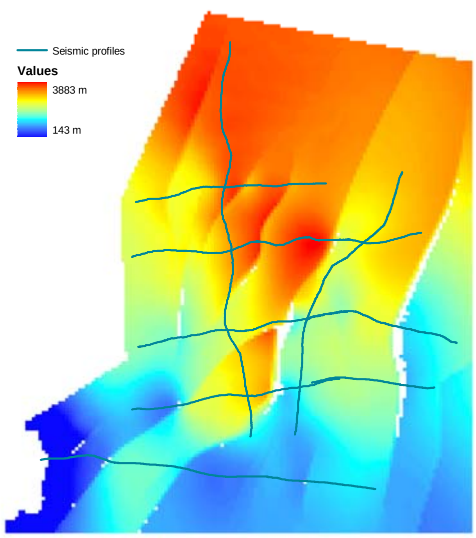

Figure 9 – Depth map of the top of Buntsandstein with a 200m mesh.

The thickness of the Buntsandstein reservoir is in average between 300m and 500m (Figure 10). At the centre of sub-basin and in the western border, the thickness reaches 1000m. However, it seems that the identified formation includes the Permian sandstones of Rotliegende and could not be distinguished easily with seismic profiles. These Rotliegende sediments are not continuous in the whole Rhine graben, but occur mainly in the North and in the graben center. They could reach around 500m thickness in the graben centre (Munck et al., 1979). These sandstones are gas reservoir in the northern part of Germany and could be geothermal reservoir, but they are poorly well-known in the Upper Rhine graben. They are generally interpreted as filling late-Hercynian grabens.

The thickness map permits to compute the volume of the formation reservoir in the studied area to estimate the geothermal potential of the reservoir. In this case with our accepted geological interpretation model (figure 8), the Buntsandstein formation including the Permian Rotliegende sandstones reaches around $300km^3$ in volume. For the rejected model (figure 9), the volume is very similar with $275km^3$.

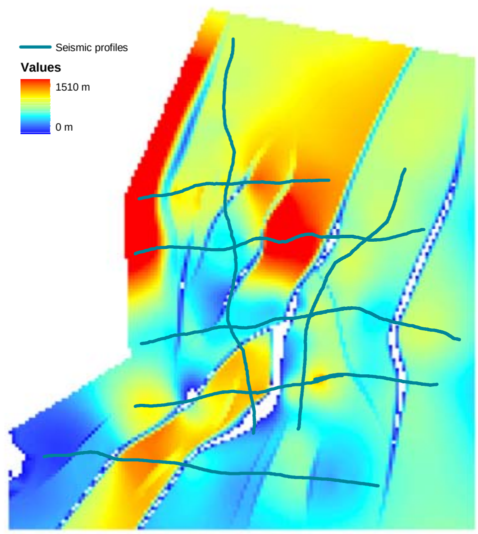

Figure 10 – Thickness map of the Buntsandstein with a 200m mesh.

The results of borehole temperature analysis combined with the geological modeling were used to compute the heat quantity as we described previously. For the Buntsandstein reservoir within the studied area and with the accepted model (figure 8), the computation gives $Q \approx 1346GW/year_{th}$.

If we consider the rejected model (figure 7), the reservoir volume will be then $275km^3$ and the heat removed will be $1224GW.year_{th}$.

In our case, the temperature factor $R_T = 83\%$ and the recovery factor $R = 27.5\%$, then the heat could be exploited is between $Q_{expl} = 337GW.year_{th}$ and $Q_{exp} = 370GW.year_{th}$ following the geological model ($337GW.year_{th}$ for the rejected model and $370GW.year_{th}$ for the accepted model).

CONCLUSIONS

The clastic formation of Buntsandstein shows a high potential for geothermal resource in the Upper Rhine Graben. This study allowed providing a preliminary assessment of this reservoir at two scales.

At the regional scale, new maps have been yielded based on previous data and the exploitable heat quantity had been computed (Dezayes et al., 2007). The northern part of the Upper Rhine Graben appears more favourable than the southern part for geothermal exploitation. The top of the Buntsandstein is at around 2000m depth where the temperature reaches about 150°C. The assessment of the heat in place gives a geothermal potential between 15 and $30GJ/m^2$. For comparison, in the Paris Basin, the geothermal potential is $7GJ/m^2$ maximum for the Dogger formation and $15GJ/m^2$ for the Trias formation (Haenel, 1989).

At local scale, some area appears favourable and their potentiality merits to be study in detail. This is the case of the south-western area of Strasbourg. We focused on a 30kmX35km area based on borehole data and seismic profiles. A 3D model of this area has been yielded to obtain the precise shape of the reservoir.

With this model, we have underlined a sub-graben located in the SW part of the area. The northern part of the area shows a different tectonic pattern with half-grabens and tilted blocks. This difference could be explained by the Southern Transfer Zone of the Rhine Graben located in the Erstein ridge and could be the continuity of the Lalaye-Lubine hercynian fault (Schumacher, 2002; Derer et al., 2005).

The interpretation of the geological area influences greatly the shape of the reservoir formation and its volume taken into account for the geothermal potential assessment. In our case, our interpretation implies a $300km^3$ volume for the Buntsandstein reservoir formation. However, we can not clearly distinguish the Permian sandstones, which are not always differentiated, from the Buntsandstein sandstones in the seismic profiles. The exploitable geothermal potential taking into account these two sandstone formations is assessed at $350GW.year_{th}$ ±20.

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