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Clastic reservoirs in the Rhine graben: geothermal potential of the Triassic sandstones based on seismic profiles and deep boreholes

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ABSTRACT

To develop the sustainable energy in France, new geothermal exploration projects have been launched in clastic reservoir of the Upper Rhine Graben. In this framework, a 30km x 32km area located between Strasbourg and Obernai has been investigated. At the scale of the Rhine Graben, this detailed area corresponds to a local geothermal anomaly and is characterized by a temperature of 100°C at 1500 m depth. The Lower Triassic layers, namely Buntsandstein formation, made of clastic sandstones represent the deep seated formations of the Rhine Graben and thus, potential geothermal reservoirs. 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 modelling sedimentary formations. According to the modelling results, different reservoir volumes have been computed which impacts the estimation of the geothermal potential.

Temperature conditions derived from BHT 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. However, the orders of magnitude of the flow rate (40l/min to 300l/min in the Buntsandstein) in the boreholes are rather low suggesting a low permeability at depth. But, numerous faults cross cut the Buntsandstein, which constitute a fractured reservoir. Consequently, flow rate could be very different from a borehole to another. Moreover, this type of reservoir could be stimulated. It is obvious that a good knowledge of the geology of the reservoir seriously impacts the assessment of geothermal potential, in terms of reservoir volume and reservoir type.

In the investigated area, the volume of the Buntsandstein reservoir is about 300km^3 and the heat potential is around 300GW/year ± 10%.

1. 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 3889.3 TJ/year with an installed capacity of 237.5MWt (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).

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.

2. 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.

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 graben, namely the Bresse and the Limagne grabens (Bergerat, 1980).

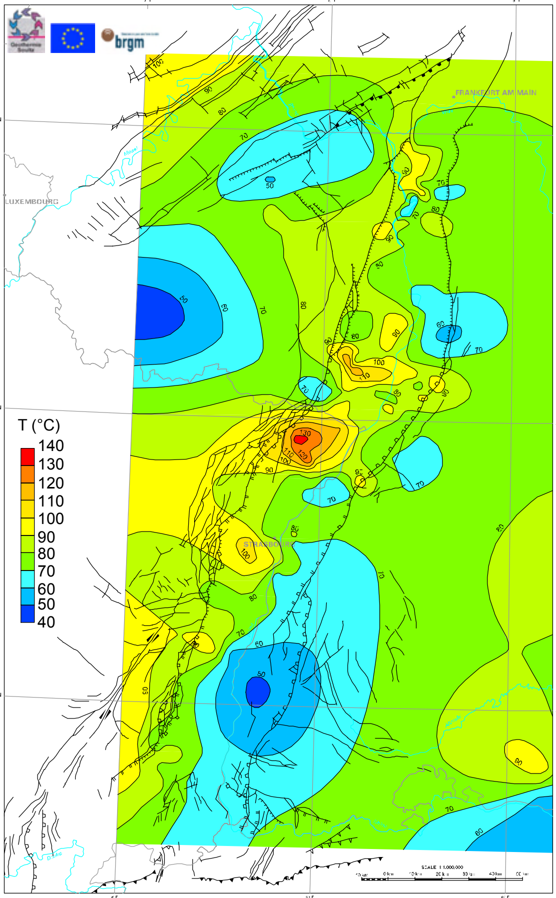

Figure 1 – Structural map of the Upper Rhine Graben and temperature extrapolated at 1500m depth (Genter at al., 2004).

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 (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 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. The studied area is about 30km X 32km 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.

3. TEMPERATURE AND FLOW IN THE BOREHOLES

The temperatures extrapolated at 1500m depth (figure 1) shows a maximum curve at 100°C in the middle of the studied zone. The shape of the thermal anomaly is elongated along the NNW-SSE direction (figure 1).

For geothermal compilation, several oil borehole data have been compiled for the Alsace area in previous studies (Vernoux & Lambert, 1993). Temperatures, flow rates and salinities are the more relevant data to determine the geothermal potential.

In the investigated zone, only bottom hole temperatures (BTH) are available in old petroleum boreholes (figure 2).

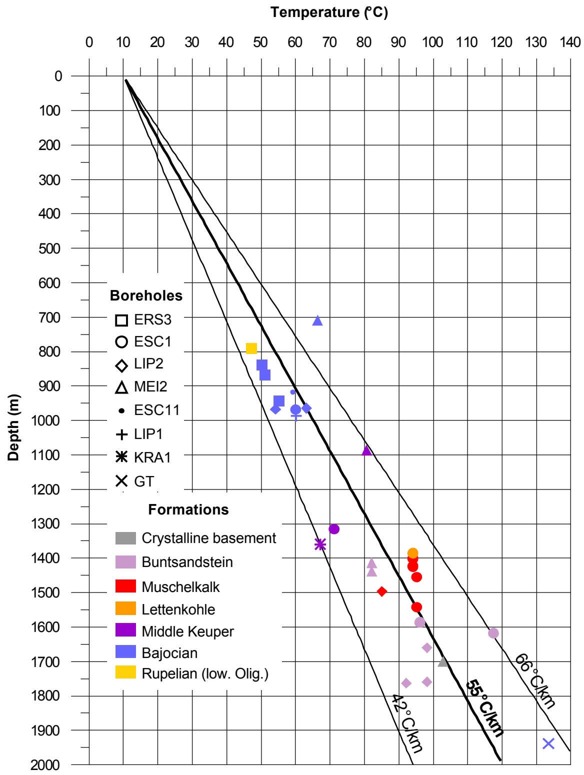

Figure 2 – Temperatures in the previous oil boreholes and calculated geothermal gradient. Boreholes are located in figure 5.

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. It is possible to correct these BHT data to calculate the undisturbed temperatures, but in our case, we don't have all parameters to do that. However, the difference between the raw BHT data and the corrected data is not of a key importance for this preliminary study of the geothermal potential. Then, these temperatures indicate a geothermal gradient ranging between 42°C/km and 66°C/km, with an average at 52°C/km (figure 2). 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 2).

The flow rates are lower than 100l/min (6m^3/h) in the limestone reservoirs of the Grande Oolithe (Upper Bajocian) and Muschelkalk (figure 3). The most important flow rates correspond to the clastic reservoir of Buntsandstein, with 300l/min (20m^3/h) in the Schaeffersheim borehole (SCS101) measuring by mud loss in the well (figure 3).

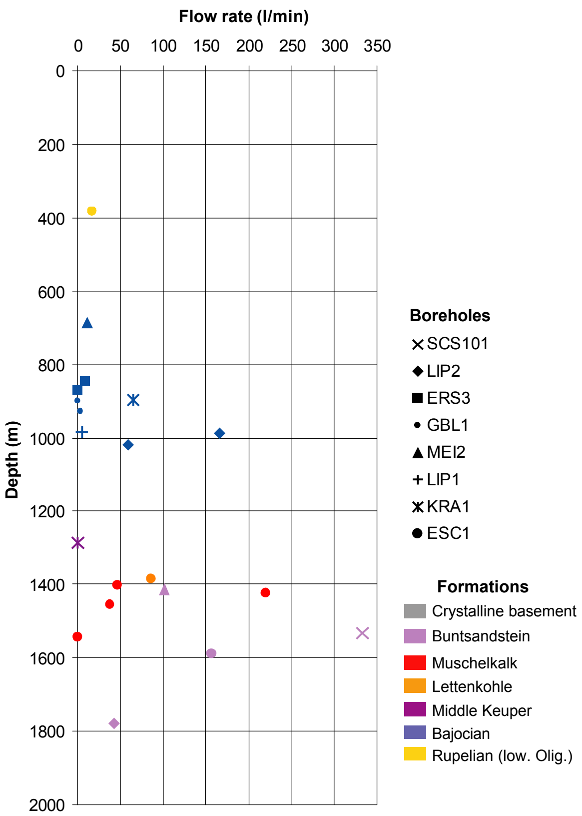

Figure 3 – Flow rates in the previous oil boreholes. Boreholes are located in figure 5.

These flow rates are too low for geothermal exploitation (in the Paris Basin, geothermal wells are producing between 100m^3/h and 200m^3/h), the measurements are not yielded in geothermal exploitation perspective and we don't know the precise well completion (often small hole diameter) and the state of the wells (presence of mud on the wall, type of mud…) when the flow rates have been measured. By experience, flow rate data measured in oil boreholes are very lower than the real flow rate, which can be drawdown from geothermal boreholes. In the Buntsandstein formation, the flow rate values range between 42l/min (2.5m^3/h) and 300l/min (20m^3/h). This expended variation is probably due to the presence of fractures, which implies strong local variability in thermal water flow. Then, the better knowledge of the geological reservoir allows improving the production flow rate. For example, in Germany, several projects have been started in the Buntsandstein reservoir at Bruschal and Speyer, where flow rates are 75m^3/h and 90m^3/h respectively (Baumgaertner et al., 2006). In the new geothermal project of Landau, the target is permeable fault zones cross-cutting the Muschelkalk, the Buntsandstein and the granite basement. This type of fractured reservoir could be stimulated by hydraulic injection in order to obtain flow rates in agreement with a geothermal exploitation (250m^3/h; Baumgaertner et al., 2006).

The salinity which is quite variable in the Grande Oolithe reservoir, ranges between 30g/l and 140g/l, with extreme values of 8g/l and 227g/l in the Grunsbuhl-1 (GBL1) borehole (figure 4). The salinity of Triassic reservoirs is moderate, with values ranging between 20g/l and 80g/l (figure 4). At Soultz, the salinity of the Buntsandstein fluids is over 100g/l (Pauwels et al., 1993) and at Bruchsal it is 130g/l (Baumgaertner et al., 2006).

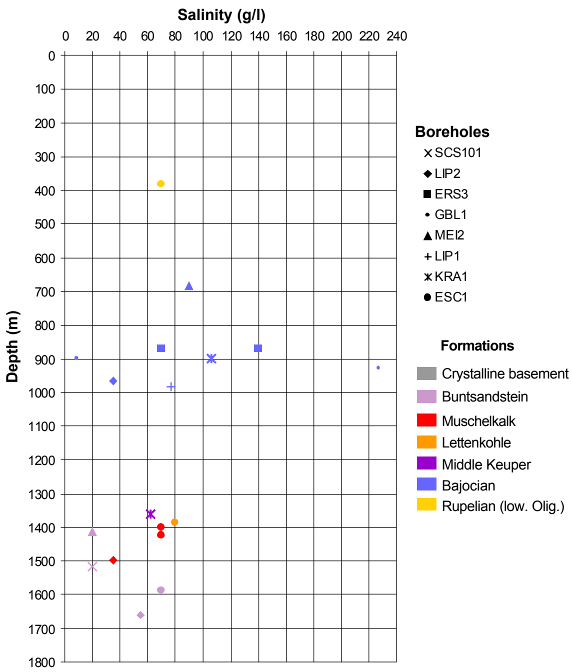

Figure 4 – Salinity in fluids in the previous oil boreholes. Boreholes are located in figure 5.

4. AVAILABLE DATA

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 5). Five seismic cross sections are transverse to the graben structures and two are oriented parallel to the graben axis that means they cross cut the first ones (figure 5). 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.

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 5). 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.

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

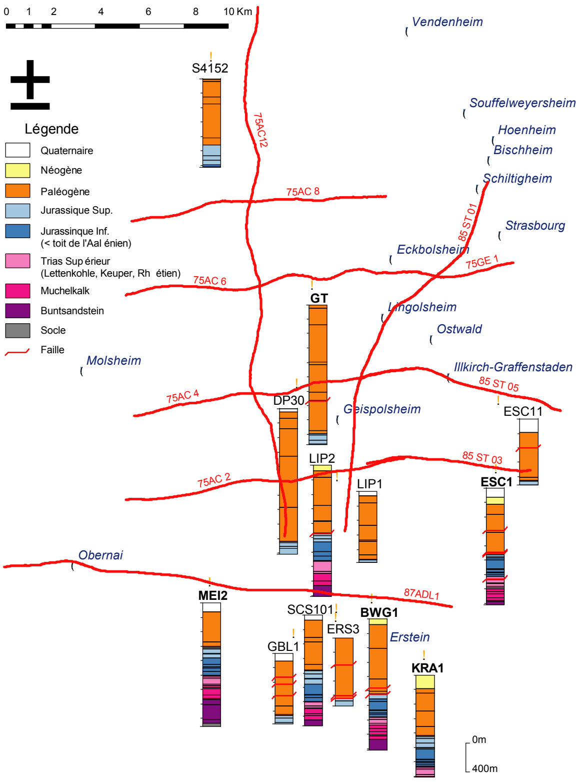

Figure 5 – Location of boreholes and seismic profiles, and geological logs in the boreholes. Boreholes with bold name have well velocity surveys.

The seismic lines have been interpreted to determine the location of faults and the limits of main formations as (figure 6):

- the top of Pechelbronn layers, which constitute a limit in the Tertiary filling sediments and correspond to a high amplitude reflector continuous within the whole graben;
- the base of Tertiary, often in unconformity with the eroded Jurassic sediments;
- the top of Aalenian, made of by a transition between limestones and marly sandstones;
- the top of Trias, made of by a transition between limestones and marls;
- the top of Muschelkalk, which corresponds to a limit between marly limestones and massive limestones;
- the top of Buntsandstein, transition between massive limestones and sandstones. This formation has a small thickness in relation to the seismic vertical resolution at this depth. Then, it is difficult to identify the top precisely;
- the top of crystalline basement, which is a low frequency reflector above a unreflective seismic facies and well-identified with a VSP (Vertical Seismic Profile).

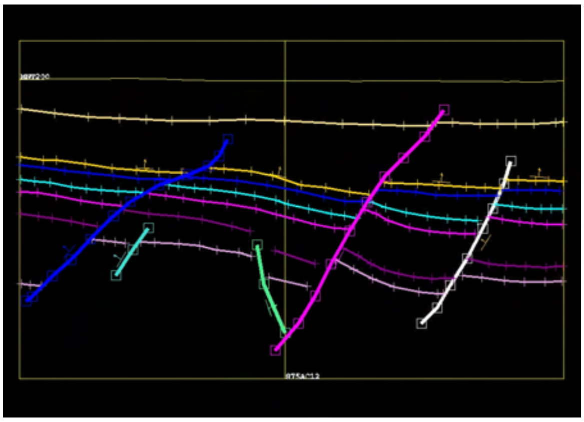

Figure 6 – Example of interpreted seismic W-E cross-section (75AC6 profile).

5. GEOLOGICAL STRUCTURES AND 3D MODELLING

On the 2D cross-sections, the sedimentary layers are crossed by numerous highly dipping normal faults. These faults prolong downward within the crystalline basement. Several minor antithetic faults are present in the Tertiary. Their apparent dip-slip fault throw can be important. The major faults show an off-set higher than 1000m and locally over 2000m. Faults often, show a differential throw between the Tertiary layers and the underlying formations. This indicates a syn-sedimentary activity of the faults during the Oligocene rifting.

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.

Thanks to the GeoModeller software developed by BRGM, a 3D model of the deep Triassic sandstone formation is outlined. The modelled 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 7). The potential field cokriging method has been used for modelling the geological interface shapes (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.

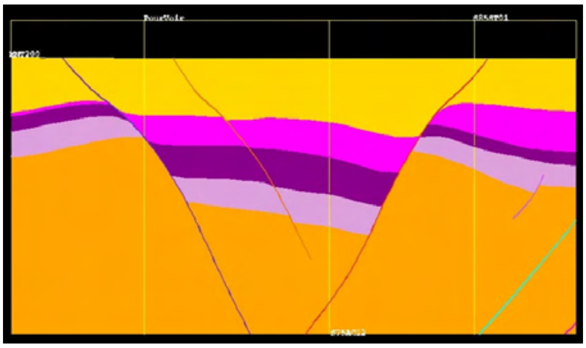

Figure 7 – Example of interpolated interfaces and faults in a seismic W-E cross-section (75AC6 profile). Yellow: Tertiary, pink: Jurassic and Upper Trias, purple: Muschelkalk, violet: Buntsandstein, orange: crystalline basement.

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 tested the effect of each configuration on interface interpolations. This leads as to retrain hypothesis which leads to the minimum intra-block distortion in the interfaces. As an example, the configuration shown on figure 8 has been rejected and we favour hypothesis illustrated of figure 9.

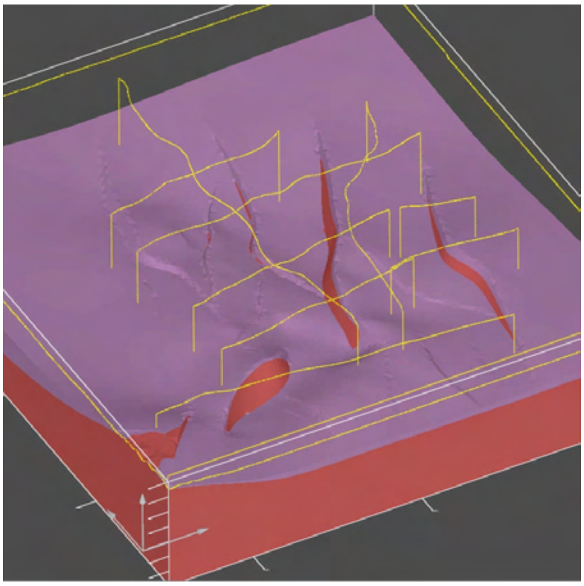

Figure 8 – View to the NE of a model, which is rejected because of intra-block distortion. Violet Buntsandstein reservoir, red: crystalline basement.

This most probable geological model shows a fault network with NNE-SSW striking orientation (figure 9). Ante-Tertiary layers are tilted to the North, like the whole Rhine Graben. 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 9).

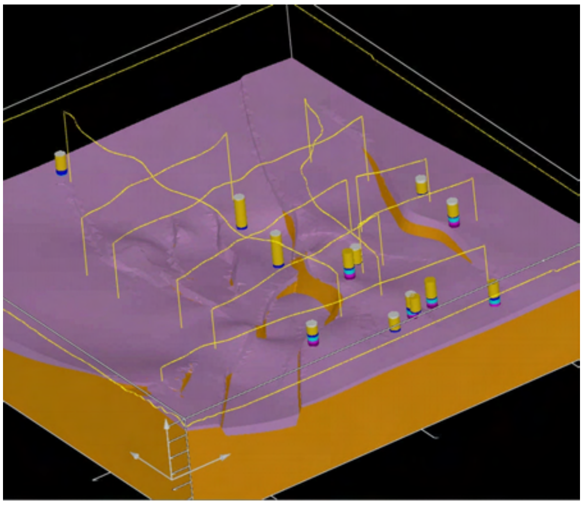

Figure 9 – View to the NE of the accepted model. Violet: Buntsandstein reservoir, orange: crystalline basement. The cylinders represent the boreholes.

6. GEOMETRY OF BUNTSANDSTEIN RESERVOIR

The Buntsandstein represents an interesting geothermal reservoir, which could be exploited for heating and/or electricity production with a low thermodynamic cycle.

Based on the accepted 3D model (figure 9), 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 in relation with the graben tilting (figure 10). 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.

The thickness of the Buntsandstein reservoir is in average between 300m and 500m (Figure 11). 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.

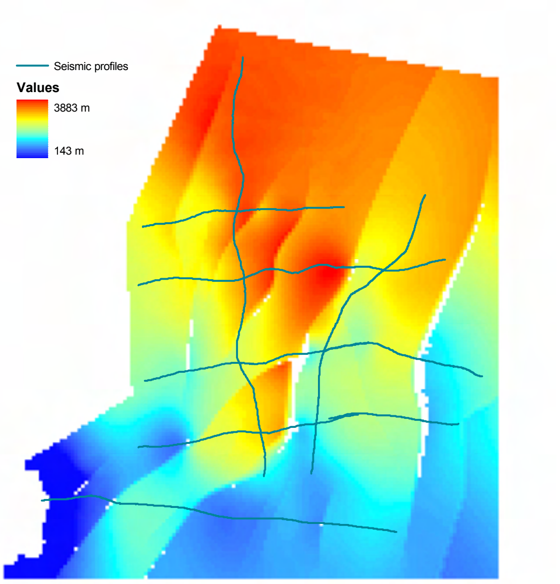

Figure 10 – Depth map of the top of Buntsandstein with a 200m mesh.

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 9), the Buntsandstein formation including the Permian Rotliegende sandstones reaches around 300km^3 in volume. For the rejected model (figure 8), the volume is lower with 275km^3.

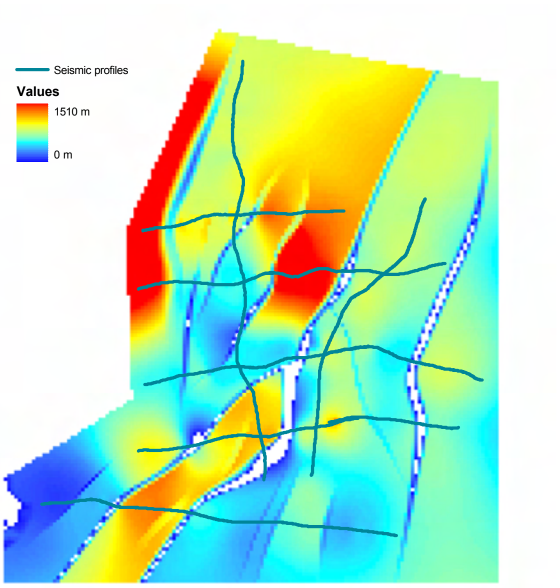

Figure 11 – Thickness map of the Buntsandstein with a 200m mesh.

7. GEOTHERMAL POTENTIAL OF THE STUDIED AREA

The results of borehole temperature analysis combined with the geological modeling described in the previous sections were used to compute the heat-in-place for the Buntsandstein reservoir. The heat removed is given by:

$$Q = \rho \, . \, C_p \, . \, V \, . \, (T_i - T_f) \qquad (1)$$

ρ: rock densities. For sandstones: $\rho = 2200$ kg/m^3

C_p: heat capacity. For sandstones: $C_p = 710$ J/kg.K

V: volume of rock. For the studied area, V = 300 km^3

T_i: initial temperature of the reservoir. For the Buntsandstein, $T_i = 90$°C

T_f: final temperature after the total exploitation of the reservoir, or surface temperature. $T_f = 10$°C.

For the Buntsandstein reservoir within the studied area and with the accepted model, the computation gives $Q \approx 38.10^{18}$J or 1188GW/year.

If we consider the rejected model (figure 8), the reservoir volume will be then 275km^3 and the heat removed will be 1089GW/year.

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):

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

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). For an aquifer reservoir, Lavigne (1978) shows that the geometric factor is 0.33, then:

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

In our case, $R_T = 81\%$ and $R = 26.8\%$, then the heat could be exploited is between Q_{expl} = 292GW/year and Q_{expl} = 318GW/year following the geological model (292GW/year for the rejected model and 318GW/year for the accepted model).

8. CONCLUSIONS

To determine the geothermal potential of the Buntsandstein reservoir in Alsace, we have studied in detail a 30km X 32km 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 subgraben 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 318GW/year.

The temperature and flow rate values acquired in the previous oil boreholes in the Buntsandstein formation give indication to the geothermal interest of the area. The temperatures reach 90-100°C and could be enough to produce heat and even electricity by new binary power plant (Köhler & Ziegler, 2006). Apparent flow rates measured in the previous oil borehole are not enough for geothermal producing. However, the Buntsandstein sandstones in the Rhine Graben are not a continuous reservoir but contain numerous large-scale faults. They must be considered as a fractured reservoir and then the production flow rates are linked to the fault pattern, forming flow paths.

In conclusion, detail knowledge of the deep-seated geology is a primary importance to define a geothermal potential area, as well as to determine the reservoir type and volume.

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