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3-D VISUALIZATION OF A FRACTURED GEOTHERMAL FIELD: THE EXAMPLE OF THE EGS SOULTZ SITE (NORTHERN UPPER RHINE GRABEN, FRANCE)

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ABSTRACT

This present paper describes a 3-D geological model in the Upper Rhine Graben, around the EGS (Enhanced Geothermal System) Soultz site (France). This model is a 30x20x6 km geological model built from the surface to the crystalline basement. The goal is to visualize the complex fault network of the graben by federating the knowledge on this specific area.

The building of the 3-D geological model is based on two main kinds of data: (1) seismic profile interpretations and (2) borehole data. The seismic profiles have been acquired for oil exploration in the 70-80's, and reprocessed recently in the framework of various projects. The 2-D information is interpolated to the whole 3-D space using a geostatistical analysis.

For our model, a network of 26 fault has been built. The orientation of the major faults is NNE-SSW (i.e. Rhenish direction), with a main eastward dipping. Secondary, principally antithetic faults, trend N-S to NNW-SSE, with an average dip of 60°. This 3-D geological model could be now used as a basis for many exploration investigations and different kinds of modelling.

INTRODUCTION

The development of renewable energy in France necessitates exploring new or poorly weel-know deep geothermal reservoirs located in promising area. In this framework, the concept of EGS (Enhanced Geothermal System) developed at Soultz since twenty years must be now extended to the Upper Rhine Graben.

The EGS Soultz site is located in the northern part of the Upper Rhine Graben (France), above an important positive thermal anomaly. The area is highly fractured due to the Cenozoic tectonic opening of the Rhine Graben. Numerous regional and local normal faults are present, most of time superimposed on previous hercynian structures. This structural network is the way for fluid circulations and probably the basis of the thermal anomaly of the area. To assemble the all the data and knowledge on this area, we built a 3-D geological model. This model allows to have a visualization of the geometry of the fault network and the deep geological formations, in order to federate people for future exploration studies (for examples gravimetric and magnetic inversions).

The building of the 3-D model is based (1) on geological investigations in the framework of the EGS Soultz project (Dezayes *et al.*, 2009), and also (2) a new exploitation of old seismic profiles acquired for oil exploration in the 70-80's. We reprocessed the profiles to improve the quality of the seismic image. This improvement was possible thanks to new algorithms, as well as in a better definition of the static and dynamic corrections. A new interpretation has been done throughout different scientific projects. The 3-D model consists in a 30x20x6 km geological model extending from the crystalline Hercynian basement to the surface, including Triassic, Jurassic and Tertiary layers.

Our study focuses on the data we used, and the building of the fault network, and presents the resulting 3-D geological visualisation of this specific area of the northern Upper Rhine Graben.

GEOLOGICAL SETTING

The Rhine Graben is a Cenozoic graben belonging to the West European Rift System (Ziegler, 1992), which is very well-known based on numerous studies for petroleum and mining exploration (boreholes, geophysical surveys…).

It is located in the extreme NE part of France for its western part and in Germany for its eastern part (Figure 1). The graben is 30-40km large and 300km long and the Rhine river flows through it.

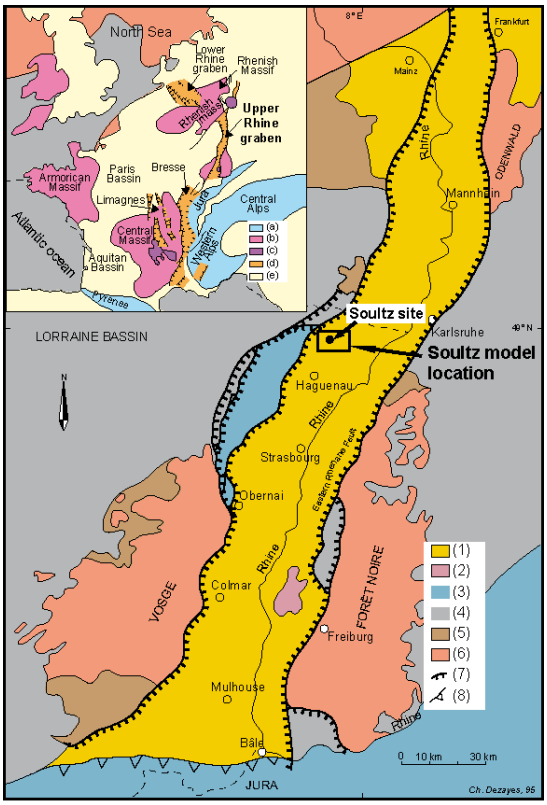

Figure 1 - Simplified geological map of western Europe and the Rhine graben with the location of the EGS Soultz site and the limits of the 3-D geological model. (a) alpin massifs, (b) hercynian massifs, (c) volcanics massifs, (d) graben filling, (e) sedimentary basin. (1) Oligocene and Miocene sedimentary filling, (2) Cenozoîc volcanism, (3) Jurassic sediments (Lias and Dogger), (4) Permo-carboniferous bassins, (6) Hercynian basement, (7) main border faults of the Rhine Graben, (8) thrusts.

The Rhine Graben is filled by Tertiary and Quaternary siliciclastic, lacustrine and few marine sediments with a rather discrete volcanic activity, overlaying the Jurassic and Triassic sediments together with the Paleozoic crystalline basement.

This graben is made of three segments limited by border faults oriented N15°E in the North and the South parts, and N30-35°E in the Central part (Figure 1). Two crystalline massifs surround it, namely the Vosges massif along the western side and the Black Forest along the eastern side. Fracture fields are located between these mountains and the Rhine valley. They are bands of fractured terrains, which collapse progressively giving a general stair-like framework (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. The latter permits to link the Rhine Graben with other Tertiary grabens, namely the Bresse and the Limagne grabens (Bergerat & Geyssand, 1980).

The opening of the Rhine graben near the late Eocene-Oligocen boundary allows to reactive the Variscan tectonic structural framework. A series of N30°E-N40°E trending discontinuous structures have been identified on gravity and magnetic maps of the Upper Rhine Graben basement, as well as in outcrops in the Vosges, Black Forest and Odenwald mountains (Edel *et al.*, 2006). These NE-SW trending discontinuities were successively reactived during the late Eocene N-S compression and the early-middle Oligocene E-W extension (Villemin *et al.*, 1986; Schumacher, 2002) as sinistral strike-slip faults and as oblique normal fault (Edel *et al.*, 2006). Elongated depocenters appears to form in association with the reactived Variscan wrench faults (e.g. the Rhenane border fault), particularly in the centre part of the graben.

During the Rhine graben formation, several major subsidence phases generated variable sediment thicknesses. The subsidence starts at the end of Eocene (Lutetian) and continues during Oligocene under an E-W extensional regime. From the Upper Oligocene (Chattian), the subsidence pattern is different in the northern and the southern parts of the graben (i.e. 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 side, 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. There, the subsidence rate is less important and the graben borders are less uplifted (Villemin *et al.*, 1986).

In connection with the rifting, the Moho was uplifted, implying a large-scale positive geothermal anomaly. Moreover, additional small scale geothermal anomalies are also due to fluid circulations within fracture zones (Pribnow and Schellschmidt, 2000). These local anomalies are mainly located along the Western border of the graben, where the fluid circulates from East to West (Benderitter and Elsass, 1995; Pribnow and Clauser, 2000). Inside the Rhine graben, several local geothermal anomalies occurred and are spatially distributed along a North-South: Selestat, Strasbourg, Soultz (in superimposition with the petroleum field of Pechelbronn), Landau (also a petroleum field), Wattenheim (NE Worms) and Stockstadt (SW Darmstadt). The thermal anomaly of Soultz is the most important with 130°C at

1400m depth, which correspond to the top of the granitic basement.

DATA USED TO BUILT THE 3-D MODEL

The model is located in the North of the French part of the Upper Rhine Graben, including the EGS site of Soultz and its geothermal anomaly. The dimensions of the model are 30km along the E-W direction, 20km along the N-S direction, and 6km deep. As the structures are overlaid by the sediments filling the graben, two kinds of data are used to build the 3-D model: (1) seismic profile interpretations and (2) borehole data.

The seismic profiles were acquired for oil exploration in the 70-80's, following the stop of the exploitation of the Pechelbronn oil field, close to the EGS Soultz site. We reprocessed these profiles from the raw data, in the framework of various projects. This new process of the seismic data was possible thanks to new algorithms, as well as in a better definition of the static corrections and dynamic corrections. This reprocessing improves the quality of the seismic image. Compared with old-processed profile, the newly processed profiles display a better (1) continuity and horizontal-vertical resolution of the seismic horizons or groups of horizons, (2) geometric characterization of faults and fault zones (Beccaletto *et al.*, 2010).

During the first stage of the EGS Soultz project, five seismic profiles, PHN84J, PHN84K, PHN84L, PHN84R, PHN84W, close to the future EGS Soultz site, have been reinterpreted (Cautru, 1988). Numerous old petroleum boreholes have been used to interpret these profiles, then to identify the seismic horizons as geological interfaces, and convert the time scale seismic profiles into depth sections (Figure 2).

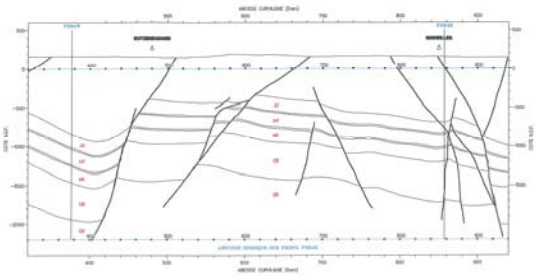

Figure 2 – Example of a geological cross-section interpreted based on seismic profiles PHN84K (Cautru, 1988).

These geological cross-sections show the detail of the structures around the EGS Soultz site. This allow us to have a good visualization of the horst structure under the EGS Soultz site, which allow to reach the granite, target of the project, at 1.4km depth. These geological cross-sections have been used to build the first 3-D geological model of Soultz (Renard & Courrioux, 1994) and the local part of our model (Dezayes *et al.*, 2009). To extend this first model, we used a larger, regional set, of seismic sections (Figure 3). These regional sections have been built by concatenation of different single old petroleum seismic profiles acquired during the same oil exploration phase as described above. However, the raw seismic data have been homogenized, and a new process have been applied to improve the image quality. Along the entire French part of the Upper Rhine Graben, about 60 transversal seismic sections have been built with around 10 km between each other, as well as 5 longitudinal sections. The interpretation of these 1600km regional seimic profiles has been done in the framework of the European GeORG project, whose goal is to improve the knowledge of the Upper Rhine Graben for the geological resource exploitation (groundwater, geothermal energy, CO_2 storage…. Capar *et al.*, 2009).

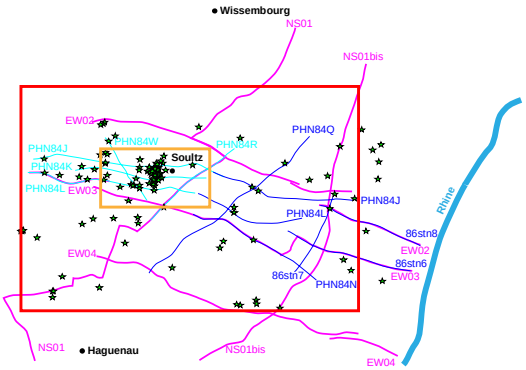

Figure 3 – Location of the data; boreholes (green stars) and seismic profiles included within the local Soultz model (orange rectangle) and the regional model (red rectangle). Light blue lines: seismic profiles interpreted in the framework of the Soultz project (Cautru, 1985), Pink lines: seismic profiles interpreted in the framework of the GeORG European project (Capar et al., 2009), dark blue lines: seismic profiles interpreted in the framework of the Roquette geothermal project.

To convert the interpretation of seismic profiles from time scale to depth scale, we used velocity data related to some of the boreholes. A detailed analyse of these velocity has been presented in Baillieux *et al.* (this issue).

We observe a high density of normal fault on the seismic sections. Most of these normal faults cross-cut the entire Cenozoic sedimentary filling of the graben as well as the Mesozoic pre-rift sediments. We also observe numerous occurrences of strike-slip features, which form negative flower structures (Beccaletto *et al.*, 2010). They are the most recent structures and may be related to the early Miocene to present NW compressional stress field (Villemin *et al.*, 1986).

In addition to the data described above, we also used the interpretation of some seismic profiles located at the eastern part of the model area. These interpretations come from an exploration study for a future geothermal project, namely Roquette project, located to the east of the Soultz site. The goal of this project will be to dry starch with geothermal steam. However, the thickness of tertiary sediments is very large in this area (more than 1000m), so that it is very difficult to interpret the deepest horizons.

The data of 64 oil exploration boreholes, coming from the French Geological Survey (BRGM) database, namely BSS (Banque de données du Sous-Sol), have been integrated in to the model. Unfortunately, most of them are shallow and mainly give information on the Tertiary and Jurassic layers. The boreholes located along the seismic sections were used to constrain the position of the interfaces. These boreholes have been drilled in the past for the petroleum exploitation of the Pechelbronn field. Where there were no seismic profiles, we used essentially the geological data from the boreholes to constraints the model (Figure 4). The data of the deep boreholes of the Soultz site have been added, in the aim to model the granitic basement (Dezayes *et al.*, 2009).

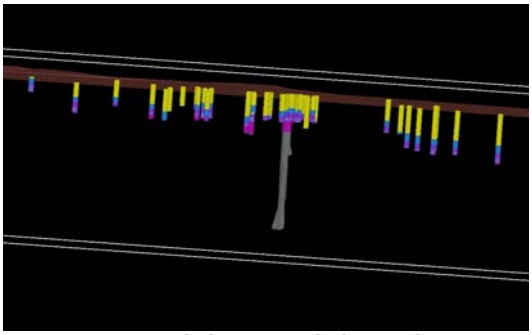

Figure 4 – Boreholes around the Soultz site. In yellow, the tertiary formations, in bleu, the Jurassic formations, in purple: the Keuper formation, in purple-blue, the Muschelkalk formation, in pink, the Buntsandstein formation, in grey, the basement. The deeper boreholes in the center represent the Soultz wells(5000m depth).

3-D GEOLOGICAL MODELLING

The 3-D geological model is built on the basis of geological map, cross-sections, boreholes and a digital elevation model (DEM). To construct the 3-D volumetric bodies, we used the 3-D Geomodeller, an original software developed by the BRGM (French Geological Survey; Lajaunie *et al.*, 1997; Calcagno *et al.*, 2008) and specifically devoted to geological modelling. Using this software, lithological units are described by a pseudostratigraphic pile, intended to image the geological and structural relationships as best as possible. Compared with other existing 3-D solid modelling approaches, a major feature of this modeller is that the 3-D description of the geological space is achieved through a potential field formulation in which geological boundaries are iso-potential surfaces, and their dips are represented by gradients of the potential. The model is built in a geo-referenced system and it takes into account:

- points, which define the location of geological interfaces or faults/fracture;
- orientations, which define the dip and polarity of geological interfaces or faults/fracture;
- a geological pile, which define the *a priori* geological knowledge about chronology and relation between the geological formations.

Our model is 30km long along the E-W direction, 20km long along the N-S direction, and 6km deep. To model the sedimentary cover, we digitized the interpretation of the seismic profiles within the cross-sections defined by the seismic profile walk-away. In this cross-section, only the location and the apparent dip of interfaces have been known, but unfortunately not the complete orientation of point data. The faults traces were digitized along each cross-section and linked from one section to the other. A fault can stop against another fault or be secant. To established associations between these tectonic structures, the 3-D Geomodeller uses a dedicated tool that links faults to faults. The same method is used to define which layers are affected by a fault. For the minor faults, we define a finished extension. Radius values limit the size and the extension of the faults within the layer and the model. Then, the software displays the fault traces on all sections. It is possible to choose which traces are the most probable when several possibilities occur. If the correlation is inconsistent, we are free to modify the interpretation, by varying the different parameters such as orientation data (dip, dip direction …), relationship, etc…. These steps are repeated until the fault network is 3-D-consistent with the geological and tectonic context (Figure 5).

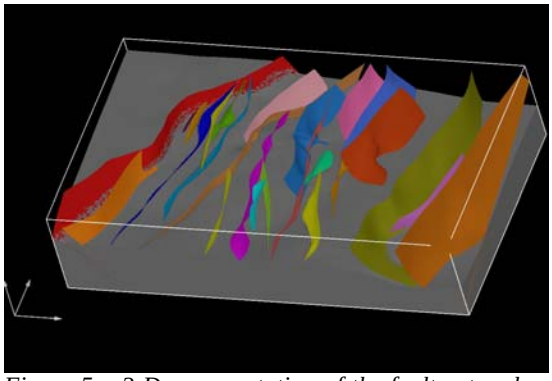

Figure 5 – 3-D representation of the fault network and the basement (in gray). In red, the rhenan border fault (dimension of the model: 30x20x6km).

We also compare our network with the former interpretation of the area done in the framework of the oil exploration (Foehn,1985).

Resulting data for each lithological layer come from the interpretation of the interfaces on each cross-section, and the geology data based on the wells. A central step is the definition of the lithological layers of the model. The original stratigraphy has been simplified: five main layers characterize the sedimentary cover of the area (Figure 6). The different deposits of the Tertiary are grouped into one layer called Tertiary. The same unification has been done for the Jurassic deposits. The Triassic sediments are represented by the Keuper, the Muschelkalk and the Buntsandstein sediments. These formations have been grouped in the Trias serie because they have a constant thickness. The deeper serie is the basement (granite). All the layers are onlap series.

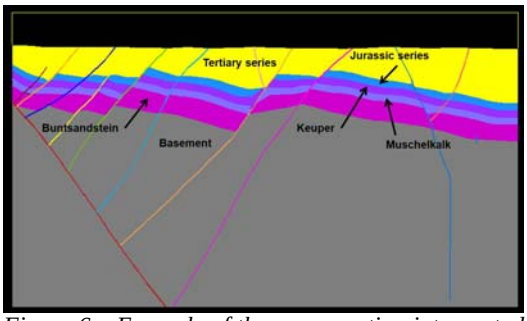

Figure 6 – Example of the cross-section interpreted based on the seismic profile PHN84J (Cautru, 1988) and the different series modeled.

Once all the data have been included, the software computes the model, by interpolating data points and orientations and taking into account the fault-to-fault and fault-to-lithological layers relationships.

REGIONAL MODEL DESCRIPTION

A local 3-D geological model has been first built around the Soultz site (Figure 3) to test the feasibility of the process with only deep data (Dezayes *et al.*, 2009).

In the extended model, we built a 26 fault network. The orientation of the major faults is NNE-SSW (Figure 7). These faults are normal faults with a high eastward dip and large extensions. This kind of faults affects all the geological formations from the Tertiary series to the basement. Inside the different blocks, minor faults were also built. These secondary faults, only cutting through the sedimentary cover, are principally antithetic faults and trend N-S to NNW-SSE (Figure 7).

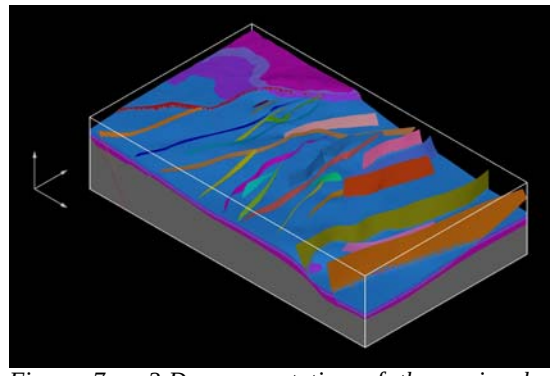

Figure 7 – 3-D representation of the regional model. In blue, the Jurassic formations, in purple: the Keuper formation, in purple-blue, the Muschelkalk formation, in pink, the Buntsandstein formation, in grey, the basement. The Tertiary series have been hidden.

A detailed analysis of this model is done in Baillieux *et al.* (this issue).

CONCLUSIONS

This paper demonstrates the usefulness to build a 3-D geological model to visualize a complex regional fault network. The present model could be now used as basis for many exploration investigations and different kinds of modelling, such as geophysical inversion, thermo-hydraulically modelling …

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