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Towards a 3D velocity model deduced from 2D seismic processing and interpretation in Northern Alsace (France)

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ABSTRACT

Since the last decade, geothermal exploitation activity in the Upper Rhine Graben (URG) has been on-going with several German, Swiss and French deep geothermal sites such as Bruchsal, Bruhl, Groβ Gerau, Insheim, Landau for Germany, Basel, Riehen for Switzerland and Soultz-sous-Forêts, Rittershoffen for France, which are active from exploration to exploitation. All these projects deal with deep fractured geothermal reservoirs located within Triassic-sediments and/or crystalline basement. Since 2011, Electricity of Strasbourg is the holder or co-holder of several exclusive lease for the exploration of high temperature geothermal fields (>150°C) in the Northern Alsace (France). This paper is part of an exploration phase, where we attempt to combine different stratigraphic models realized for four exclusive licenses (Soultz-sous-Forêts, Rittershoffen, Wissembourg, and Lauterbourg) using a modeling software. In a first step, this paper aims to harmonize reprocessed seismic sections interpretation derived from several acquisitions through time within a unique model in order to compile each unique interpretation of the four licenses within a same Northern Upper Rhine Graben 3D model. In a second step, velocity data acquired during drilling campaigns have been used to estimate the local interval velocity of major interpreted geological formations. This time-depth relationships data allowing a conversion from a time based model to a depth based model. Such an outcome has various geothermal applications. For example, it allows the location of induced seismicity in 3D structures representing a significant improvement of events location or it can be used to constrain interpretation of results obtained by other geophysical methods, such as potential methods.

1. INTRODUCTION

For more than twenty years now, the Upper Rhine Graben has been a main target for research on geothermal exploitation in deep fractured rocks. Indeed, the scientific pilot site at Soultz-sous-Forêts, established in a deep fractured granitic massif between 3.5 and 5 km depth has resulted in the development of the Enhanced Geothermal System (EGS) technology and has provided the international scientific community with a unique high quality data set (Genter et al. 2015a). The principle of the EGS technology consists in increasing the low natural hydraulic performance of the geothermal fractured reservoir by thermal, hydraulic or/and chemical stimulations. These stimulations increase the fracture permeability to allow pumping the geothermal brine at economically viable flow rates (Baujard et al 2015, Genter et al. 2015 b, Maurer et al 2015).

In such development context, ES is the holder or the co-holder of four exclusive research licenses in Northern Alsace, France: the so-called "Soultz", "Hatten-Rittershoffen", "Wissembourg" and "Lauterbourg" licences (Figure 1). For a duration of 5 years after granting, multiples data have been acquired thanks to exploration campaigns, such as seismic surveys, and drilling programs, all driving to geo-scientific reports. In particular, vintage seismic profiles have been reprocessed on all licences (for Lauterbourg license see Fonta 2014), leading to individual stratigraphic models. In this paper, we intend to perform a numerical modeling built from the integration of seismic and well-log data in a unique model. We compared several former seismic interpretations realized during decades of exploration phases. Based on these previous works, a new harmonized time-based 3D structural model was created. From geophysics acquisitions, various type of velocity information was used to feed the model such vertical seismic profile (VSP), sonic logs and checkshots. Moreover, it leads for specific wells to the creation of a time-depth-relationship (TDR), linking velocity to time data. Indeed, the well loggings performed on the Rittershoffen site allows refining the initial velocity function derived from Soultz-sous-Forêts site, leading to an accurate local interval velocity function. Voxelization of this synthesis 3D model was performed and fed with velocity information allowing to convert the 3D model from time to depth. Such an outcome has various geophysical and geothermal applications.

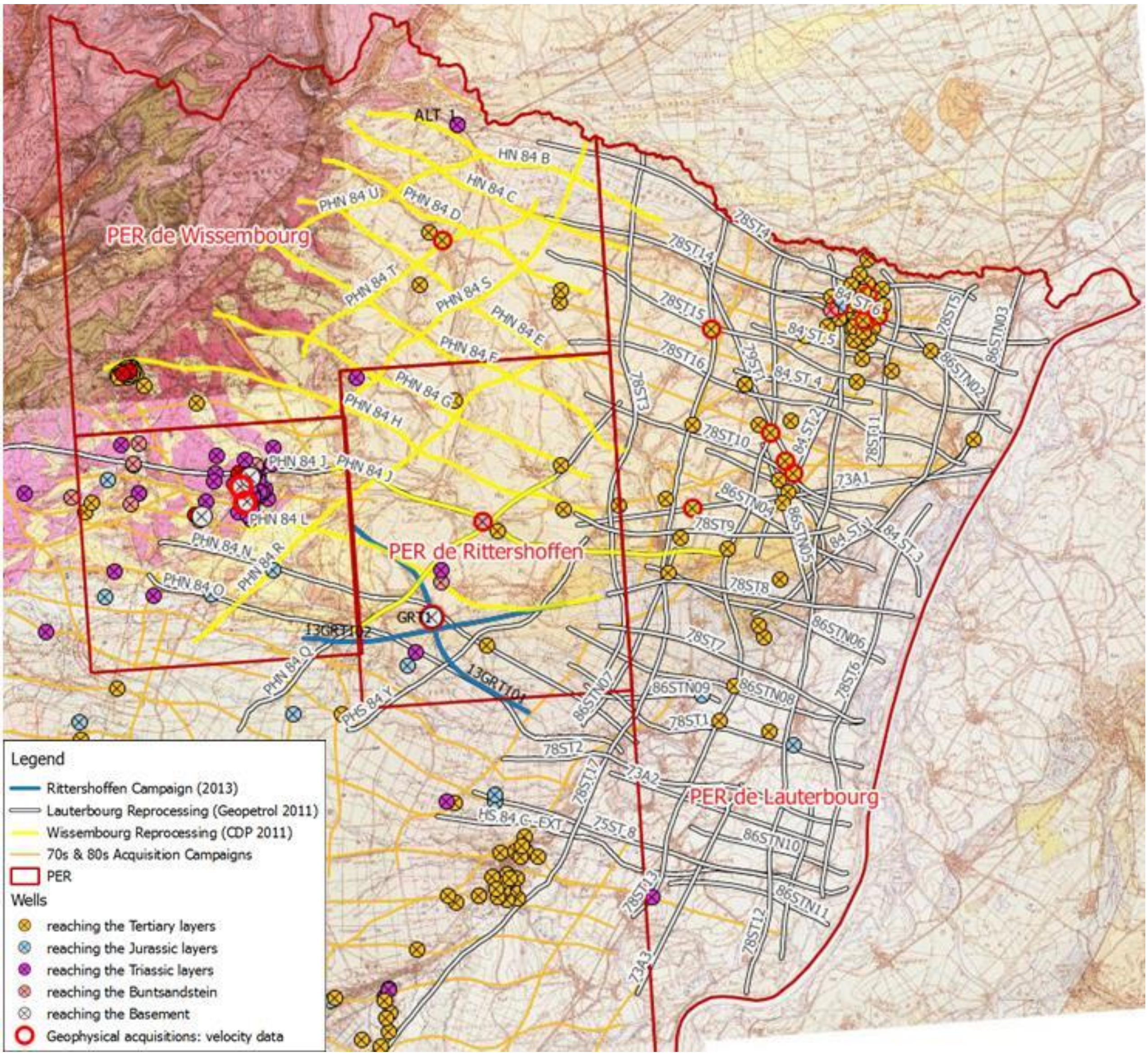

Figure 1: Licenses owned or co-owned by ES and considered seismic lines.

2. GEOLOGICAL SETTINGS

The Upper Rhine Graben is a 300 km long, 40km width regional rift zone with an azimuthal orientation averaging N020°E between Mainz and Basel (Figure 2). It is associated to the Rhine plain structurally bounded on the South by the folded Jura, on the West by low relief Vosges mountain range, on the East by the Black Forest and Northward by the Vogelsberg volcanic massif.

The western edge of the Rhine Graben is limited by two major normal faults. The outermost Vosges fault separates Paleozoic series from Mesozoic series and has variable vertical off-sets from several hundred meters to over a thousand meters. The innermost Western Rhine fault inconspicuous on the surface separates Mesozoic series from Cenozoic series. On the Eastern shoulder of the URG, the Schwarzwald fault and the Eastern Rhine faults are dipping westward with similar vertical off-sets.

Stratigraphically, the uppermost part of the Rhine Graben is composed by Plio-Quaternary deposits which uncomformably cover Eocene and Oligocene formations whose deposition began during the regional extensional context started 40 My ago. This extension is at the origin of the spacing between the Western and Eastern regional Rhine faults. The sedimentological filling of the basin is syn-tectonic and affected by numerous normal faults resulting from the opening system. Within the Mesozoic era, lack of Cretaceous sequence is observed in the Upper Rhine Graben due to a late Jurassic uplift phase, resulting in a 125 Ma hiatus in the depositional sequence (Figure 3).

The Mesozoic and Paleozoic formations, in continuity with the Paris Basin, are exhumed in the rift flanks and are buried below the Tertiary cover, deeper in the center of the graben by tilted blocks. Detailed lithologic studies have been performed from the GRT-1 borehole during Rittershoffen drilling operations (Aichholzer et al 2015).

For geothermal issues in the Rhine Graben, propitious targets are mainly deep and fractured hard rocks. Natural fracture system governs natural permeability. Boreholes analysis in the Rhine Graben has shown the permeability of the matrix of the deep formations is too low for a geothermal exploitation. Furthermore, each borehole with high productivity rates is associated with natural faults/fractures induced by the tectonic evolution of the Region.

Depending on the local geological conditions, the fractured permeability's efficiency is enough to allow a water circulation and/or its pumping exploitation (Le Carlier et al 1994). It explains, in case of a interconnectivity, that the circulation could be at regional scale, allowing fluids to reach greater depths (roughly 4-5km; Sanjuan et al 2016) and temperatures, generating higher temperature gradients than in a classical sedimentary basin. Geothermal brine acts as a heat transfer fluid by pulling up the heat towards the shallower formations through convection cells. The geothermal fields of Soultz-sous-Forêts and Rittershoffen confirm the presence of warm and deep circulations (Baujard et al. 2015, Dezayes et al 2015, Genter et al. 2015b, Sanjuan et al 2016). Thus, a litho-stratigraphic knowledge is required for an optimal location of the production platform to reach deep-rooted structures where the potential fractured reservoirs are in the shallowest position.

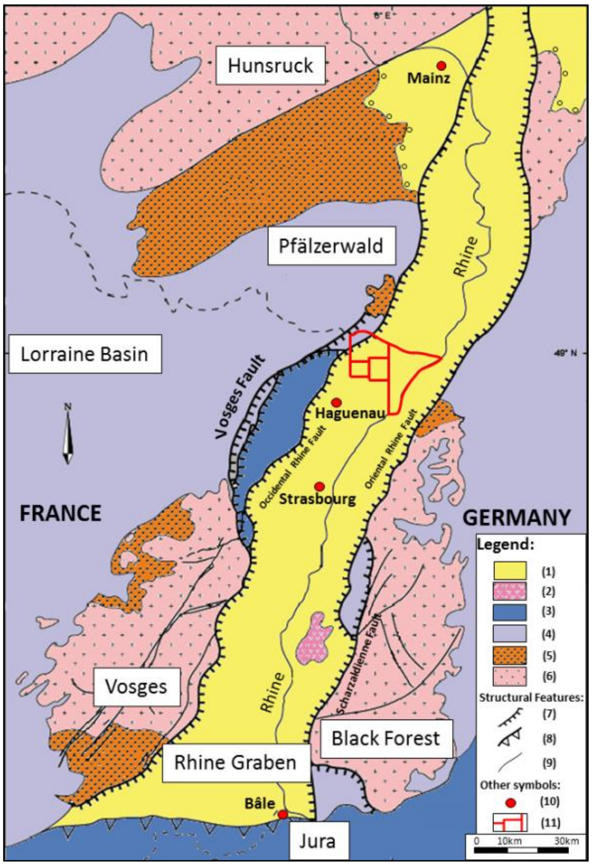

Figure 2: Simplified geological map of the Rhine Graben with the locations of ES permits (Modified from Genter et al 2003). (1) Oligocene and Miocene sedimentary filling, (2) Cenozoic volcanism, (3) Jurassic sediments (Lias and Dogger), (4) Mesozoic basin, (5) Permo-Carboniferous basins, (6) Hercynian basement, (7) main border faults of the Rhine Graben, (8) Thrusts, (9) Undifferenciated faults, (10) Cities, (11) ES Exclusive research licenses.

3. SEISMIC ACQUISITIONS AND PROCESSING

3.1 Seismic campaigns

The oil historic past activity of the Northern Alsace implied that many 2D reflection seismic lines were acquired since the 50's mainly for petroleum targets located in the superficial Tertiary layers. Furthermore, high resolution seismic reflection (2D-HR or 3D-HR) stays the most convincing geophysical method to obtain an accurate litho-stratigraphic model in the sediments, and in particular for extrapolating fracture zones visible at the top basement, used to define a potential geothermal target.

However, this geophysical method isn't adapted for basement rocks which, due to its nature, do not have the seismic response of horizontal reflectors. And so, faults embedded into the basement are deduced from the knowledge obtained during decades of exploration campaigns. Many seismic profiles and boreholes exist within the four exclusive licenses (Figure 1). However, acquisition methods used for oil and gas exploration into the Tertiary formations are not fully adapted for deep geothermal targets. Nevertheless, innovative seismic processing methods have emerged in the last decades, driven by increasingly efficient computer capacities. In the framework of geothermal exploration, 64 vintage 2D seismic lines were reprocessed with nowadays technics to image the fractured/faulted zones into the sedimentary formations. A particular attention has been paid to faults with significant apparent vertical off-sets located at the interface between the clastic sediments and the top crystalline basement. Afterwards, the interpretation and the interpolation of each seismic lines lead to a time based stratigraphic model.

3.2 Previous interpretation works

The 64 seismic lines reprocessed in this study were acquired in the 70s and the 80s and cover the “Wissembourg”, “Lauterbourg” (Fonta 2014), “Hatten-Rittershoffen” and “Soultz” licenses. Two additional seismic lines dedicated to the Rittershoffen project were acquired and processed in 2013 within the “Hatten-Rittershoffen” license. Bibliographic research on independent interpretation programs was performed and five imported data sets were considered all previously processed and interpreted independently, nevertheless all of these data sets suffer from certain limitations (Figure 4).

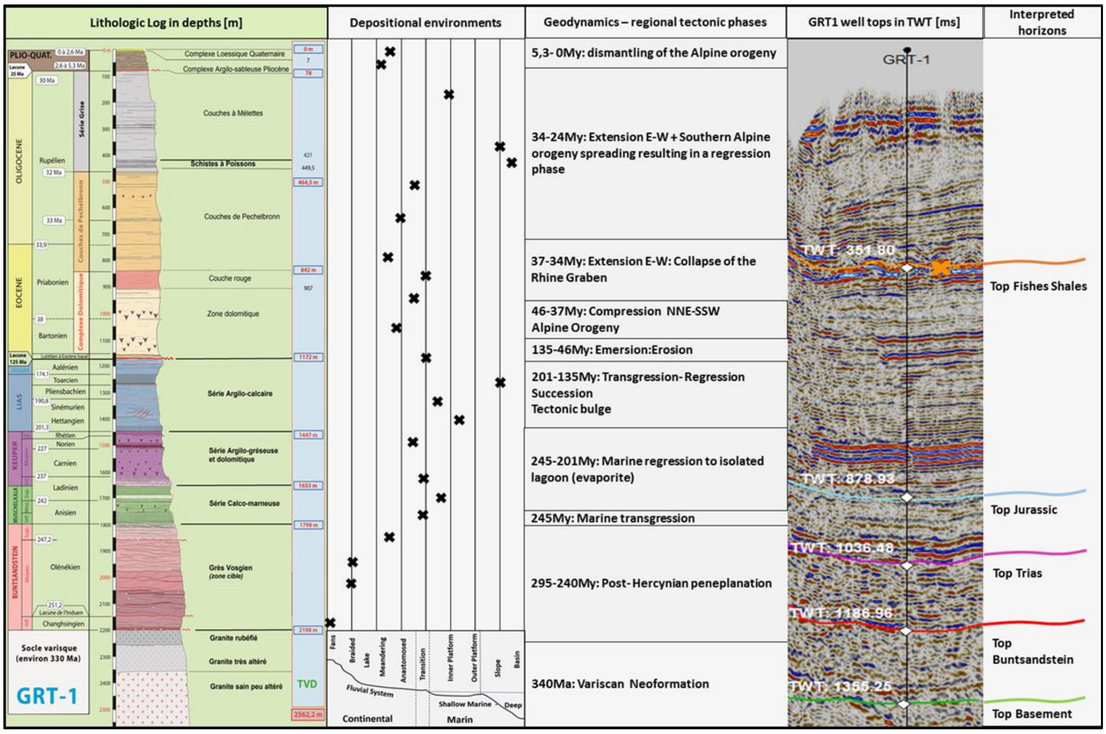

Figure 3: Comparison between (on the left part) stratigraphic log, depositional environments and tectonic context expressed in True Vertical Depth (TVD) [m] and (on the right part) interpreted horizons expressed in Two-Way Time [ms] (modified from Aichholzer et al 2015).

	Sources	
Consulted interpretations	Dylikowski J., 1985. Étude en stratigraphie sismique de remplissage Tertiaire de la région de Péchelbronn: application au développement pétrolier en domaine de fossé d'effondrement. Thèse de doctorat d'Orsay, Paris, France, 248p.	
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	C. Dezayes & Al., 2011, 3D visualization of a fractured geothermal field: the example of the EGS Soultz site (Northern Upper Rhine Graben, France), Conference paper, Thirty-Sixth Workshop on Geothermal Reservoir Engineering Stanford University, California.	
	Sources	**Critics**
Imported Models	Depth based Structural model establish for the GeOrg's project (http://www.geopotenziale.org/home).	Made for the entire Alsace region, only a few seismic profiles in the PER of Wissembourg have been considered. Separation between interpreted profiles is consistent and thereby fault's assignation may be unreliable
	Time based Structural model establish by Total (1985) (Foehn, 1985 et Wannesson, 1998), following the seismic campaign realised by the CGG company (1984)	Time based modeling has the effect of slightly distorted angles and the lateral positions of the faults, and so any interpretation in depth could be dangerous
	Depth based Structural model establish by the CDP Consulting (2011) following the reprocessing of the Wissembourg PER's seismic profiles.	In the Wissembourg area, this structural model is the more accurate one, due to its depth based interpretation and because it includes all seismic lines in this license. However, interpretation inconsistencies were noticed.
	Time & Depth based Structural model establish by Geopetrol in the Lauterbourg's PER (2013)	In the Lauterbourg area, this structural model is the most completed one because it includes all the seismic lines located within this PER (64 lines). As for the model of CDP, inconsistencies were noticed.
	Time based Synthesis Structural Model establish by ESG attempting to unify the structural models of all mining permits in the Northern Alsace.	Initially performed by L. Plévy in 2014, funded under the project EGS Alsace, it is in this purpose we try to build a consistent 3D model

Figure 4: General table listing the main consulted previous interpretations.

An exhaustive import data session was performed by Plevy (2015). This consisted in grouping seismic files (SEGY format), the interpretations files (horizons and faults) associated to different studies and data from wells drilled (trajectory, stratigraphic markers, crossed faults, well logs). All data were referenced in a common system of 3D coordinates. Finally, in the framework of this work, former models were compiled, examined and reinterpreted to ensure the continuity and the homogeneity of horizons and fault surfaces from one model to another. All models were eventually merged to build a regional 3D consistent stratigraphic model.

Common data processing is the key point in order to carry out the execution of a homogeneous model. For geological interpretation purpose, model in depth deduced from TDR is required. The three basic operations performed in seismic processing (stack, migration, conversion) can be realized in different orders. Preference was given to the prestack time migration (PSTM), given that each section of the area was at least reprocessed in this way. The operations were executed as follows: time migration - summation - depth conversion. The time migration requires only an approximate velocity model and improves the readability of seismic images by repositioning reflectors to ensure their continuity. The summation is then facilitated. The prestack time migration of the data provides more confidence in the zone of interest for geothermal purpose. The quality of seismic sections has been considerably improved for Cenozoic and Mesozoic formations; however Paleozoic deep targets stayed poorly imaged.

4. NUMERICAL MODELLING AND DEPTH CONVERSION

4.1 Interpretation description

From the former seismic interpretations studies as well as from older models imported into Petrel software, a phase of re-interpretation was necessary in order to build a unique, consistent and homogenous 3D model through the 4 exclusive research leases. For the geothermal purpose of this study, no interest in the description of all seismic reflectors was discerned. So a decision was taken to interpret individual reflectors, a time saving strategy for the interpretation of the 64 seismic profiles. The seismic sections polarity used during the interpretation is "SEG normal" meaning that an increase of the acoustic impedance corresponds to a positive amplitude peak.

Five main horizons have been picked. The reflection of each is characterized depending on its geometry, its termination and its configuration (see Figure 3):

- The Oligocene horizon "Top of Fish Shales" corresponds to a high amplitude peak continuous and undisturbed. This reflector is easily recognizable although it is locally subject to some variations in interpretations.

- Next highlight horizon is the "Top of Jurassic", representing the erosional top of the Mesozoic formations. This is a negative peak of high amplitude with a relatively good continuity. This reflector is usually located after a series of three high amplitude reflections, even if this unconformity is a rarely seen in seismic, in particular under the plans marked by listric faults which are rooted in the salt layers and anhydrite levels located at the base of the Cenozoic formations. The Jurassic seismic unit is composed by formations from the Aalenian to the Rhaetian which marks the transition to the top of the Triassic. The unit is a transparent seismic facies with geometry of reflection of low frequency and variable amplitudes corresponding to calcareous intervals (Kirwiller, Zinswiller, and Gundershoffen).

- The horizon “Top of Trias” corresponds to the marl-calcareous lithologic transition. Several exploration wells have been targeting Triassic formations (Oberroerden 101, Rittershoffen 1-2-3, Donau 1-2). In comparison with well data, seismic is often inappropriate for these depths. The seismic signature is a positive amplitude peak located at the base of an energetic series.

- The horizon “Top of Buntsandstein” corresponds to the calcareous-sandstone lithologic transition, we attempt to identify this specific horizon for geothermal issues. It is a positive amplitude peak, often discontinuous. It has a variable quality reflection according to the studied section. Reflection seems to be in a parallel configuration, no specific termination was discerned.

- The horizon “Top of basement” corresponding to the top of the altered crystalline basement. Vertical Seismic Profile (VSP) acquisition on the OBER101 well enables the calibration of the top of the basement with the acoustic basement response on seismic sections which is a very low frequency.

Hundreds of faults have been picked into the seismic profiles interpretation. Here, after the assignment step, four categories of main faults were identified depending on their continuity and their importance:

- Major faults reaching the basement: they affect the entire sedimentary thickness; rooting and depth extension is not fully characterized. It is easy to assign the fault from a seismic line to another thanks to an important displacement observed.

- Mesozoic faults: they do not affect the Tertiary series (only detectable under the erosive horizon "Top of Jurassic"): They define ante-tertiary blocks, structured in horst and graben.

- Tertiary listric faults: they are rooted in the salt layers and anhydrite levels located at the base of Cenozoic formations, considering as major regional accidents that rejection up to over 1,000 meters. In some cases, the fault plane can even be associated with a reflector (i.e. line HS84Cext).

- Tertiary faults: they only affect Tertiary formations and are mostly related to the activity of major accidents previously evoked.

4.2 Time based Structural model

From the final interpretation on the seismic profiles composed of the five picked horizons and the assigned faults, a time-based synthetic 3D model was built (Figure 5).

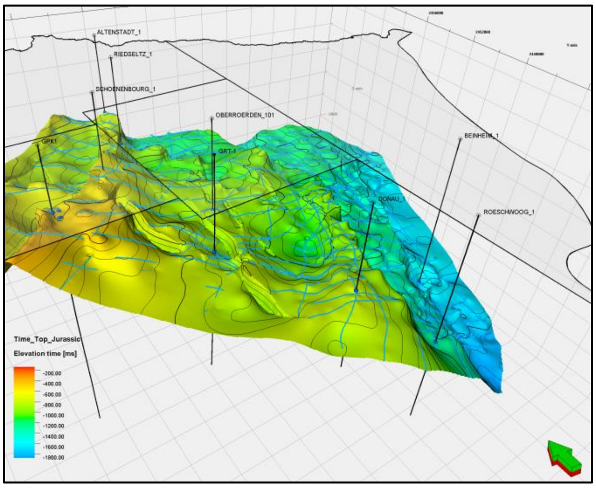

Figure 5: Example of a 3D time-based surface of the top of the Buntsandstein, built from interpreted horizons (blue lines).

4.3 Creation of the TIME DEPTH RELATIONSHIP (TDR)

In order to create a TDR, only velocity information coming from wells logging, such as VSP, sonic log or check-shots was used. A first approach is to use an average velocity method. From the interpretation of horizons, a time-based map is generated and an average velocity is calculated between the seismic reference datum (SRD) and the picked horizon at each well that reached the formation. The result is an average velocity map for that enables the conversion from time to depth of the top of the formation. This is repeated for each interpreted horizon. A solution is to take into account the fault polygons grid the average velocity maps. This method can be used for quality check (QC) and can be useful to have a quick idea of investigation depths. Nevertheless, this approach cannot be used in 3D cases, since velocity data is only valid for interpreted horizon and not for an entire 3D model.

A second approach consists in using interval velocities (see Figure 6). Velocities information related to both checkshots and sonic logs enable us to estimate interval velocities between the 5 selected horizons of this study. However, in this approach, the presence of non-vertical faults with important offsets generates significant lateral velocity variations. For that reason an intensive work has been performed to check and eventually correct horizons in the vicinity of faults. The average interval velocity approach also takes into account velocity information available at wells, but the velocity information can be laterally extrapolated all across the area. The result is a series of laterally varying interval velocities associated to the interpreted formations. This approach is suitable in a 3D approach. However, by using interval velocities, the computation of a depth surface is highly dependent of its overlying surface and thus providing possible error propagation.

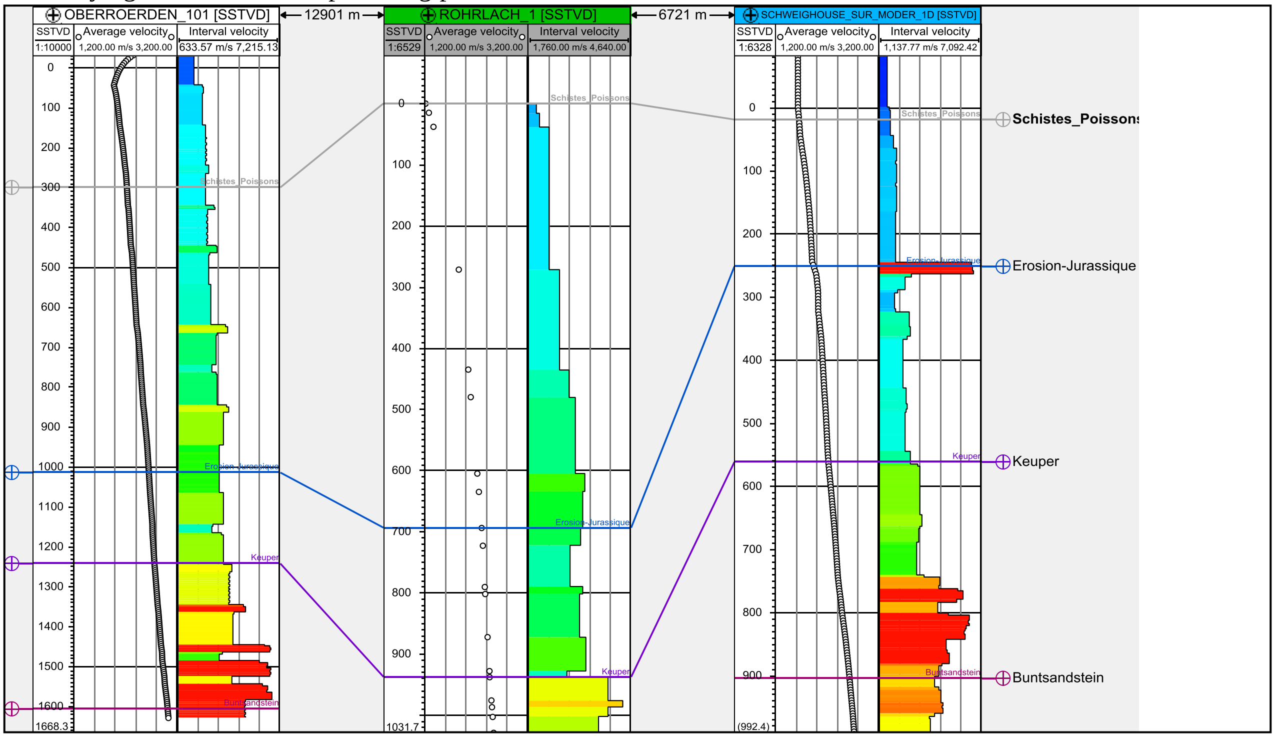

Figure 6: Well section showing average velocities, interval velocities and corresponding well tops on three specific wells (OBR_101, ROH1 and SHM1D).

For both approach, the main limitations are coming from spatial coverage of the wells that may causes uncertainties during the lateral interpolation process. But, by using interval velocities, the algorithm is able to manage the presence of faults, a velocity gradient into formations, and the depth variation of the formation, providing a more realistic approach to the interpolation between wells (Figure 7).

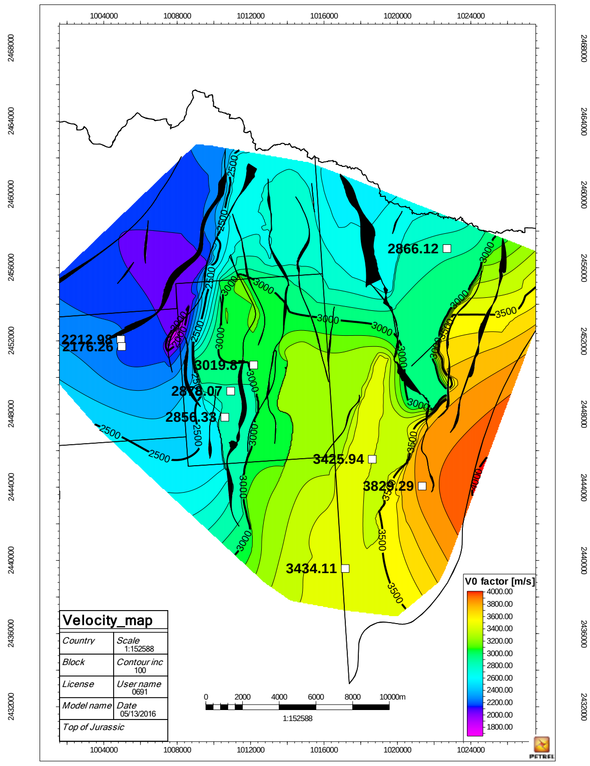

Figure 7: Velocity surface of the Top Jurassic computed from interval velocity

4.4 Gridding and voxelization of the depth-based structural model

Main interest in the modeling consists in having a velocity value at each x, y, z positions. To be able to voxelize the depth-based structural model, a time to depth conversion was first needed. A first gridding was performed, to apply the TDR previously defined to convert the whole model into depth.

The URG undergone several geological events during its formation causing variation in the organization of the sedimentary deposits of every interval. These variations have to be taken into account during the gridding process. It could be managed by changing the partition parameters. Tertiary sediments were defined as to be filled with 5 layers of cells in proportional disposition. Vertically, the entire sedimentary thickness will be expressed according the five cells which can be compressed or stretched. With this methodology, the thickness variation observed in these formations due to the regional extension regime will be taken into account in the gridding. Mesozoic sediments from the top of the Jurassic to the top of the Basement have been set as to follow a base, defined by the lower surface of each zones. Cells will be organized to fit the top of each formations surface. With this partition, it was noticed that the cells framework honors the stratigraphy (Figure 8).

The creation of a velocity model is part of a separate model in the Petrel software. The aim in this process is to produce a velocity model that will convert into depth the 3D grid such that the grid ties to the well tops. Time surfaces from the 3D grid honoring the geology was turned on, seismic datum (SRD=100m) was used as reference for the propagation of interval velocities. A careful quality checking of the input velocity model was needed.

			Time based 3D model	Voxelized 3D model
	Horizons	Division	Number of 3D cells	Number of 3D cells
Zone1	Datum Top Fishes Shales	Proportional 5	95 360	1 180 144
Zone 2	Top Fishes Shales Top Jurassic	Proportional 5	95 360	2 286 529
Zone 3	Top Jurassic Top Trias	Follow base	209 792	2 212 770
Zone 4	Top Trias Top Buntsandstein	Follow base	152 576	2 507 806
Zone 5	Top Buntsandstein Top Basement	Follow base	209 792	2 729 083
		Total :	762 880	10 916 332

Figure 8: Numbers of cells created for the time-based model to perform the TDR and number of cells of the final depth-based model after voxelization.

Every zones defined by the interpreted horizons were converted according to interval velocities implemented during the velocity model process. Well tops of wells located in the studied area, can be integrated into the project and allow a good quality control of the depth-based 3D model (Figure 9).

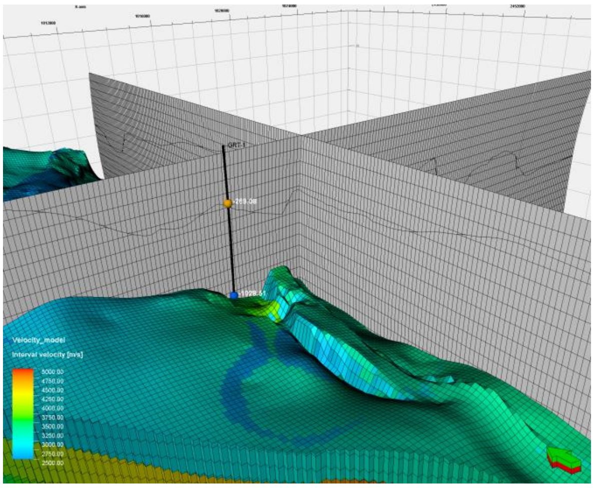

Figure 9: Gridding process consisting in the creation of zones between defined surfaces allows conversion into depth by using a TDR. Depth of the top Jurassic surface with well tops (colored circles) enabling a quality control on the outcome

In order to be able to locate seismic events into the 3D depth-based structural model, a new gridding was performed. Called the voxelization process, the outcome is a seismic cube constituted of orthogonal voxels (cells). The value x, y, z of every voxel is fixed beforehand and independent of the geologic intervals such that the vertical and horizontal thicknesses are equivalent to 100m. The flat Datum surface (+ 100m) was chosen as a base surface to the formation of voxels.

Afterwards, from the voxelized 3D grid, the interval velocity at each cell (X, Y, Z, and V) could be extracted. The gridding in cubic voxels of 100 m leads to a significant increase in the number of cells compared to the time-based geological model honoring the geology (Figure 8).

3. CONCULSIONS AND OUTLOOKS

This 3D synthesis model is an on-going step to characterize the geothermal potential of the Upper Rhine Graben. In this paper, we attempted to combine different stratigraphic and structural models realized for four exclusive licenses owned, or co-owned, by the ES (Electricity of Strasbourg) company, by using a modeling software. In a first step, this paper aimed at harmonizing reprocessed seismic interpretation derived from several acquisitions through time within a unique project in order to compile each unique interpretation of the four licenses within a same Northern Upper Rhine Graben 3D model. In a second step, velocity data acquired during drilling campaigns has been used to estimate the local interval velocity of major interpreted formations. This time-depth relationship has allowed converting the time-based model to a depth-based model.

The main improvements could be made in the accuracy of velocity models particularly in areas where the velocity data distribution is too sparse for an optimal constraint. In addition, the interval velocity technic used in this study has some limitations. The defined intervals based on the seismic interpretation and the velocities settings represent sometimes a thick layering. Thereby, to avoid vertical averaging of the velocity causing artefacts in the stratigraphic and structural model, a refining of the interpreted horizons should help. Finally, a low well spatial coverage causes uncertain lateral interpolation during the velocity's diffusion through a specific interval. Mainly employed in the petroleum industry, new numerical algorithms exist allowing a better propagation of velocity data in a 3D model. Called Volume Velocity Modeling, it detects thinner vertical layers to account for the existing velocity intervals and easily integrate seismic velocities.

Such an outcome has various geothermal applications. New research working directions focused on the location of the induced seismicity could be derived from it. Indeed, location of induced seismicity in 3D structures representing a significant improvement of event location. It will also be used to constrain interpretation of results obtained by other geophysical methods, such as potential methods currently performed in Northern Alsace. This study will significantly contribute to geothermal exploration allowing to define more accurately future drilling targets in deep and fractured hard rocks.

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