Upper Rhine Graben Deep Geothermal Reservoir Imaging

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Summary

Over the past 35 years, geothermal projects have been developed in the Upper Rhine Graben (URG) to exploit deep geothermal energy. Underneath roughly two kilometres of sedimentary deposits, the deep target consists of a granitic basement which is highly fractured and hydro-thermally altered, having a high geothermal reservoir potential. In order to better understand large scale faulting and ensure the viability of future geothermal projects, a 3D seismic survey was acquired in the French part of the URG during the summer of 2018.

This paper describes how a combination of dedicated seismic processing, imaging and interpretation can help in the understanding of this complex basin for geothermal purposes. By revealing the deep granite layer and its complex associated fault network, this helped to accurately locate future production wells.

Introduction

The Upper Rhine Graben (URG), with its deep-seated fault systems, is well known for its high geothermal potential (Dornstadter et al., 1999). This area is characterized by several local thermal anomalies associated with hydrothermal convective cells that circulate inside a nearly vertical fracture network in the granite basement and the Triassic fractured sediments above it. Sausse (2007) showed the value of seismic imaging for a comprehensive understanding of the deep underground structure for the URG geothermal project. However, the previously available seismic data in this region were acquired many years ago for oil and gas exploration (Durst, 1991). These datasets, having a different objective, are not well suited for geothermal exploration given their insufficient low frequencies (sweep starting from 10Hz) limiting wave penetration below granite basement. Moreover, most of these seismic acquisitions are 2D lines. Given the strong complexity of the fault network in URG, Eichkitz et al. (2009) showed the importance of using 3D seismic data to increase reliability of the model and image. To identify new production drilling locations a dedicated 3D wide azimuth seismic survey was acquired by Électricité de Strasbourg in 2018 (Richard et al., 2019) using a broadband low frequency sweep (2 Hz to 96 Hz). While potentially able to image the faults and fractures in the granite basement, the relatively sparse acquisition grid and lack of near offsets makes it hard to determine the shallow seismic velocities and to attenuate the noise from elastic waves propagating in the shallow section. This results in sub-optimal image of the deep faulted structure (Figure 1). In this paper, we discuss how these challenges can be successfully addressed.

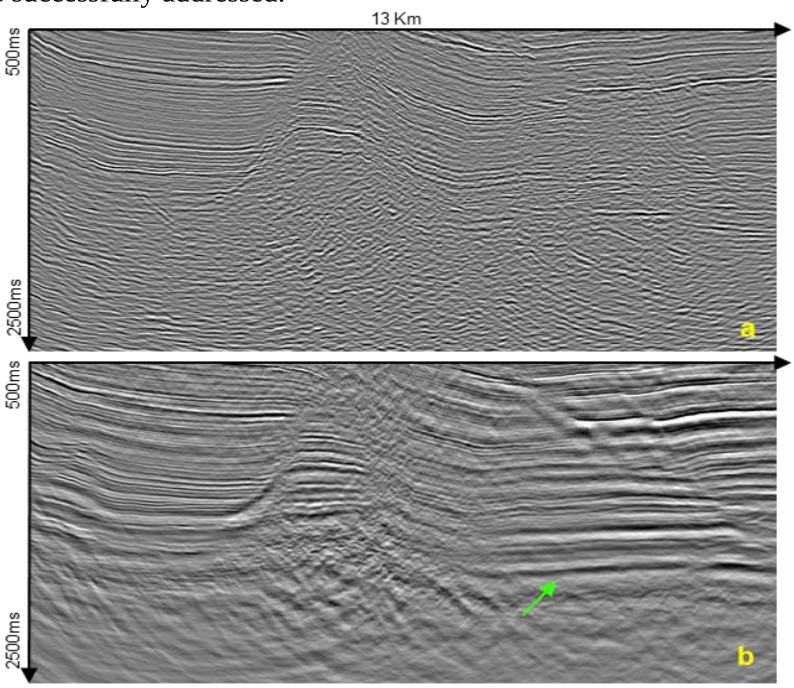


Figure1: *(a) Vintage result from 2D acquisition compared to 3D broadband acquisition (b). Top granite basement (green arrow) is now visible and trackable on the full area.*

Solving the sparse shallow subsurface sampling

Clean, low frequency primary reflections are needed to image the deep granitic basement, and so attenuation of recorded elastic waves propagating in the very shallow layer was particularly important for this project. With a relatively sparse receiver grid design (200m x 40m) and a weathering zone **(**WZ) layer with seismic velocities down to 250m.s^{-1}, recorded surface wave energy was heavily aliased in the cross-spread domain. De-aliasing of the surface waves was critical to our ability to model and remove this unwanted seismic energy. To accomplish this, we performed Spatial resampling from 10 & 20m to 2.5 m along both the receiver and source lines using a joint low-rank and sparse inversion (Sternfels et al. 2016). As surface-wave velocities vary over the survey location and are dispersive, it was necessary to use different velocities for each frequency. Using the densely sampled data, we applied a data-driven interferometry method (Chiffot et al. 2017) to produce an accurate low frequency model of the ground roll. This model was finally adaptively subtracted from the data to produce a dataset relatively free of shallow elastic-wave noise.

In parallel to the seismic reflection survey, campaigns of seismic refraction and up-holes were carried out to provide a multi-layer geological model of the unconsolidated layers. This model, containing layers which vary in both velocity and thickness, was used to derive static corrections which were applied prior to the main pre-processing and imaging flows. Although the model was calibrated where up-holes were available, the lack of near offset primary reflections, needed to image the shallow subsurface, made assessment by QC migration of our geological model difficult away from the well control points. This issue was mitigated by using information contained in the multiple reflections bouncing between the recording surface and the strong contrast at the WZ base, whose depth varied from 0 to 40m. This information was extracted via deconvolution operators. The reconstructed shallow surface layer (Retailleau 2015) allowed us to better model the velocities and QC the reliability of the WZ (Figure 2 a, b, c).

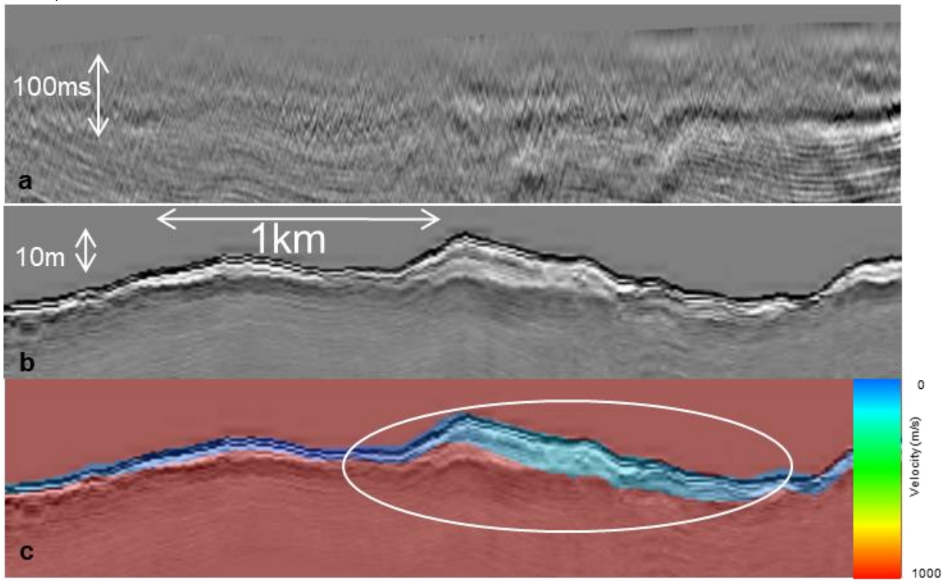


Figure 2: *Time migrated seismic section with datuming from topography to final datum (300m, Vrep 1800m.s^{-1}) as recorded (a), reconstructed shallow layer from deconvolution operators and stretched back to depth with geological model velocity (b) and with velocity model below the acquisition surface up to the WZ base (c).*

Below the shallow consolidated layer delimiting the end of the WZ, the refracted P-waves, which penetrated the deeper layers and were recorded on the longer offsets were inverted to build the first hundred meters of the velocity model. First arrivals were picked for each shot point and fed into diving-wave tomography. The resulting velocity model was compared to the well sonic log and showed a similar trend. Although this method only updates velocities down to several hundred meters, it is key for obtaining the shallow velocity variation, which is critical for the subsequent deeper velocity update.

Fault dedicated imaging

In order to assess the imaging quality of the deep faulting, each step of the pre-processing flow was validated by 3D migrating the full cube. These volumes were delivered to interpreters, ensuring regular feedback. A 3D structural model (Figure 3a) was used both as a QC and as a guide for the imaging team. Iteratively built from picked faults and key horizons on delivered volumes, the 3D structural model was built according to the results of an Advanced Fault Enhanced (AFE) volume (Figure 3b). The AFE volume is derived from a coherence cube, and greatly helped fault picking and imaging (Dorn, 2019). The ultimate goal of this model is to locate future production wells so that they cross the main faults which drain injected hot water. To refine the fault definition and location, a fault-oriented velocity model building was carried out, using and refining interpreted information to guide this work.

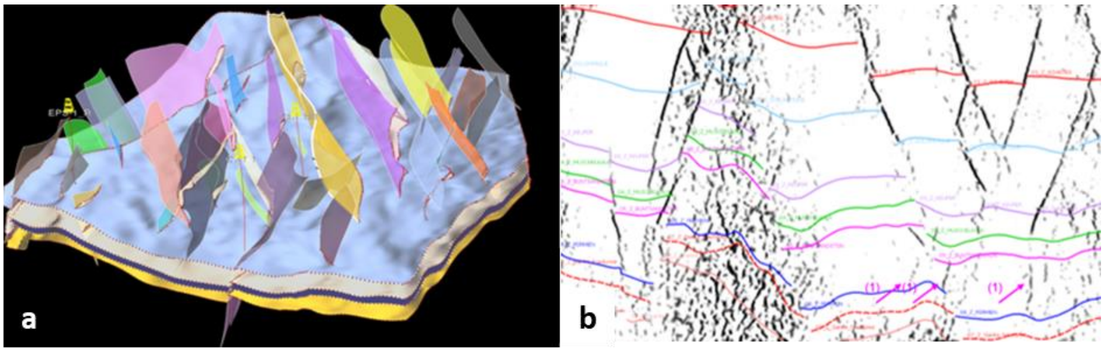


Figure 3*: (a) 3D structural model and (b) Advanced Fault Enhanced (AFE) cross section, iteratively interpreted during the imaging project. This enables well locations to be designed to cross major fault planes.*

After estimating the velocities for the shallow layers, those for the deeper part of the section were estimated using multi-layer tomography (Guillaume et al., 2012). This tomographic workflow allows each layer to be parameterized independently and helps to obtain a more accurate result, especially in the presence of sharp velocity breaks. For this purpose, geological horizons were interpreted. On this project, three horizons were defined as key for the velocity model building as they marked strong velocity contrasts. We used well-ties and velocity trends to QC the velocity updates with the help of wells present in the region.

During the inversion, to overcome lateral smoothing across faults where large velocity variations may exist, we used a fault constrained update. For this purpose, the main fault planes were picked and provided to the tomography, in addition to the above-described horizons. Introduction of this contrast in the velocity field for the pre-stack depth migration (PSDM) improved flattening of events on each side of the fault and sharper imaging of the fault planes. For the granite basement velocity, we carried out scans along with limited well information where available. Because previous wells had been drilled for oil exploration purposes (shallower targets above 1.5 seconds), only one well provided access to the granite basement velocity. The updated velocity model was then used for the final imaging. Inclusion of the fault interpretation in the tomography allowed for improved imaging of the fault planes, allowing it to be tracked more easily on the depth-slice; however; noise from the migration response still remained locally.

All the pre-processing, denoising, amplitude compensation and regularization were dedicated to correctly image the deep fault network present in the granitic layer. However, the remaining noise, the complex velocity model and the imperfect acquisition design caused visible migration artefacts. These artefacts are the results of unbalanced illumination. In order to make fault interpretation more efficient, we performed a least squares Kirchhoff PSDM (LS-PSDM). As described by Guitton (2004), this method aims to correct for migration artefacts coming from an incomplete description of the wave propagation and irregularities in the input data. Figure 4 shows reasonable attenuation of migration smiles with improved imaging of the underlying structure. This noise attenuation also re-enforced real fault energy further helping their interpretation.

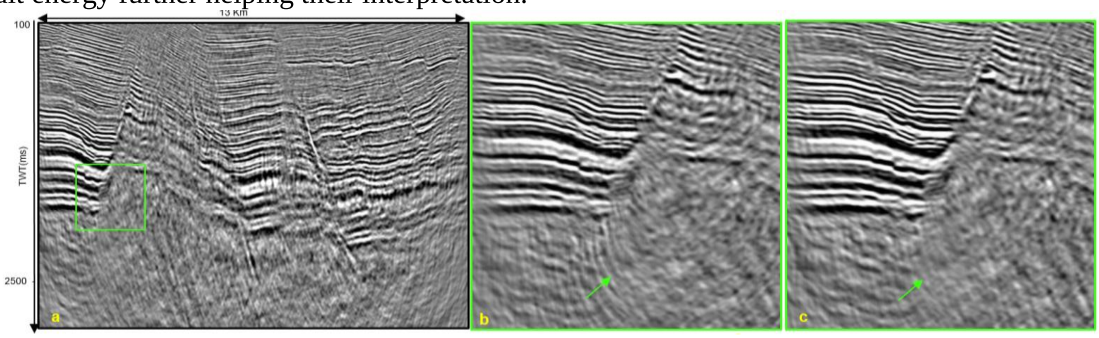
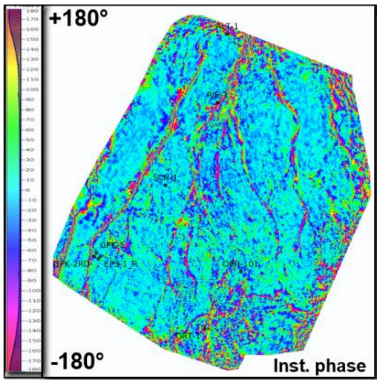


Figure 4: *LS-PSDM stack full section (a) and close up on the migration artefact of Final PSDM (b) vs LS-PSDM (c). LS-PSDM allowed to better distinguished fault over background noise and shows an uplift on the deeper fault definition*

Geothermal reservoir interpretation



Besides fault and horizon picking on the final seismic and the AFE volumes, the dedicated processing sequence also enabled deriving a robust instantaneous phase attribute (Figure 5). This attribute is able to highlight, for the first time in French part of the Upper Rhine Graben, an important fault network on seismic data inside the granite basement. The final interpretation of the fault characterization has been achieved through azimuth and dip volumes leading to a better understanding of fluid transfer inside deep basement.

***Figure 5**: Instantaneous phase at the top of granite, highlighting the regional fault network on this layer*

Conclusion

A seismic acquisition campaign was launched in 2018 by Electricité de Strasbourg over the French URG with the objective to fully image the deep granitic basement and its associated faults. Its deep target design and the very low velocities of the shallow subsurface were particularly challenging. The use of information in the multiple energy and elastic wave densification were able to resolve these difficulties. First break, multi-layer and fault constrained tomography were necessary to deliver a velocity field, maximizing common image gather flatness and minimizing mis-ties with the wells. Throughout the processing, multiple 3D migrations were performed for Quality Control purposes, in order to ensure a final accurate image of the deep part of the URG structure. The final volume shows great improvement compared to vintage image and allowed for the creation of an accurate complex 3D structural model.

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