High Resolution 3D seismic image from geothermal, jointly designed acquisition and imaging

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Summary

Seismic imaging has proven to be critical to mitigate risks during sub-surface resource exploitation. Its ability to image large 3D areas with high resolution down to several kilometers of depth allows for better localization of targeted resources, more accurate volume estimations and enhanced well trajectories; however, the quality of the seismic image greatly depends on the quality of the acquired data and subsequent processing and imaging. To optimize the seismic image quality, joint planning of the survey acquisition design and the data processing for a targeted objective is key for quantitative interpretation of the reservoir and to improve the drilling efficiency. Such collaborative planning, common in the oil and gas industry, has been successfully implemented during the North of Alsace geothermal campaign which took place from 2018 to 2019.

This paper describes how we exploited the synergy between survey design and data processing to meet geothermal objectives of interpreting the deep crystalline fault network. The image obtained can then be used to build a structural model for planning new production wells.

Introduction

The use of seismic imaging to de-risk and optimize geothermal production has been well illustrated by Richard et al. (2019). Designing acquisition parameters to attain an optimal image for a targeted part of the subsurface is an established method in the oil industry, and many acquisition designs have been implemented in order to overcome possible seismic imaging problems such as salt (Branston et al., 2020), basalt (Zhou et al., 2014) or thin reservoirs. The geothermal industry must tackle, now and in the future, similar challenges, such as having to image complex basaltic formations (Neupane et al., 2014) or deep fault networks inside crystalline layers (Dornstadter et al., 1999). The industry may also need to operate in dense urban areas, and adapt the acquisition design to surface constraints, like cities, roads or fields.

It is with this objective that Electricité de Strasbourg and CGG designed the North Alsace seismic survey project. The Upper Rhine Graben (URG) geothermal reservoir is located below two kilometres of sedimentary deposits and consists of a granitic basement which is highly fractured and hydro-thermally altered. To optimize the imaging of these faults and factures, we implemented a well-tested combination of acquisition parameters and data processing technology. This paper explains how seismic acquisition parameters can be defined considering the practical constraints, the geological target to image and the data processing to be applied.

Combining acquisition design and data processing expertise

Northern Alsace has already been imaged with 2D seismic lines in the late 1980's for oil & gas (Durst, 1991). Given their limited-azimuth geometry and lack of low frequency data content, these lines are not of sufficient quality to be used for geothermal purposes (Figure 1). Before further developing the geothermal activity in the URG, a new seismic acquisition campaign was approved.

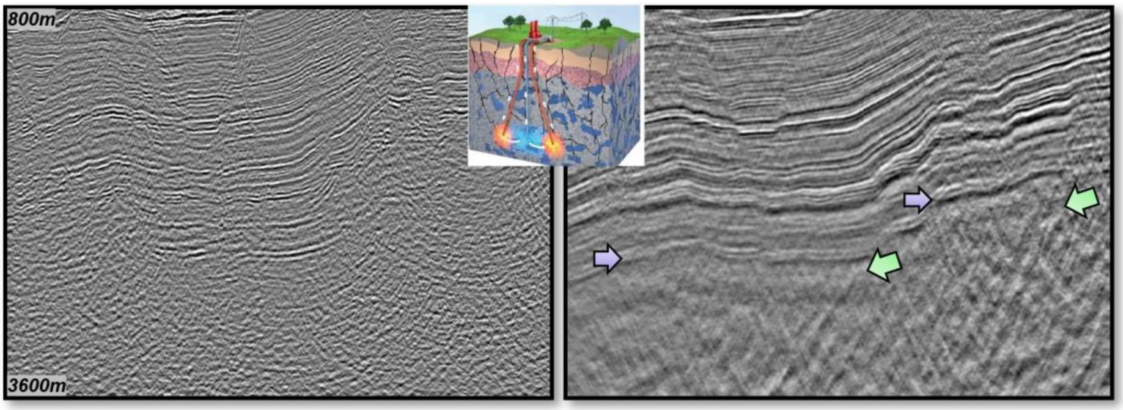

Figure 1 *Vintage 2D line (left), is compared with a random line extracted from 2019 3D volume combining new acquisition and imaging (right). Top of crystalline basement (violet arrows) is now traceable all along the section, key fault information (green arrows) is also visible. This new seismic image assists with correctly locating injection and production wells, necessary for geothermal electric powerplant activity.*

Preceding the new campaign, we performed a work of survey design, with the main goal to fully reveal the deep granitic fault network. The depth of these target faults is between 2-5 kilometres, and the strong reflectivity of the overlying granite interface will be detrimental for the signal to noise ratio (S/N). Indeed, most of the energy transmitted into the ground will either be attenuated with depth or reflected by the large impedance contrast at the sediment/crystalline interface. A particularly soft weathering layer, recognised on a previous up-hole campaign, will also absorb much of the signal. As absorption is stronger for the high frequencies, it is important to produce a strong low frequency signal. Consequently, a 2-96 Hz frequency bandwidth sweep was retained for this acquisition. Having such large low frequency content in the data then requires extensive data processing in order to fully separate energetic surface waves, considered as noise, from reflection waves used for imaging. We describe some of these details below.

To overcome the ambient noise energy coming from the urban environment (cities, roads, farming activity), it is desirable to emit a strong signal using a powerful source to obtain a satisfactory S/N at the deep target. However, having a powerful source will also generate strong surface waves. Additionally, these strong surface waves can damage the shallow, a significant problem in urban areas. Michou et al. (2017) showed that trace density, and hence the number of shot points, can drive S/N more than source strength does. Taking this into account, we chose a dense shot coverage, with variable source strength, dependent on the location of habitation in the vicinity. For economic constraints, we applied a random sweep blending (Meunier and Bianchi, 2005), which allows a large number of shots to be acquired within a short timeline. This blended acquisition leads to a preliminary step of source separation, done by the processing team, before starting a more conventional imaging project. Having access to continuous recording can also be turned into an advantage when using interferometry to retrieve very low frequency information (Le Meur et al., 2020).

Even if the main orientation of the Upper Rhine Graben structure is well known, the deep faulted network has never been properly imaged, and we expected this fractured basement to have faults with various orientations. A wide azimuth (WAZ) survey is the most suitable design in such a case, as it will be able to record more seismic ray-paths than any narrow range of azimuths. This leads to an improved image and valuable azimuthal information, useful for anisotropy characterization and definition of the fracture network. Recording the WAZ travel-paths will also be important to create the velocity model, especially to recover lateral velocity contrasts linked to large fault planes (Figure 2). In addition to the large azimuth information, long offset-data is crucial to implement Full Waveform Inversion (FWI), further refining the velocity model and the imaging of complex structures. In this acquisition, we retained a maximum offset of only 4000m, which does not allow diving waves to reach the deep target; therefore, velocity model building was done by combining refraction and multi-layer reflection tomography.

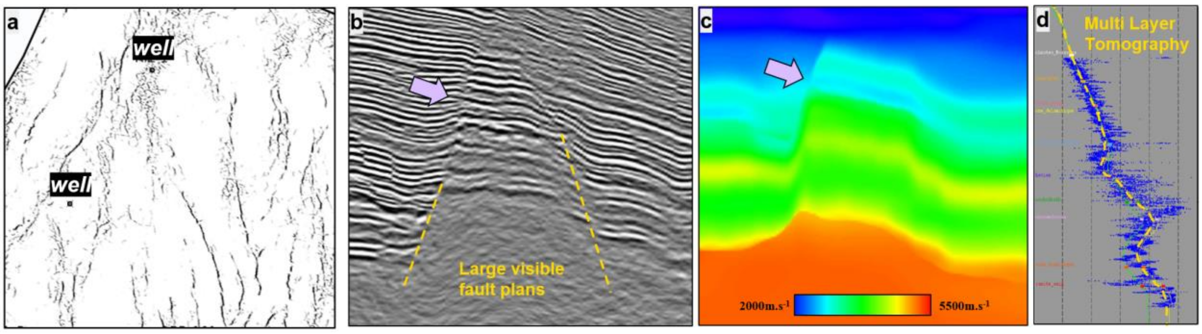

Figure 2 *Variable mapped fault dips (a) do not allow a preferred acquisition azimuth. Having WAZ information allows an inversion for a detailed velocity field, capturing velocity breaks (b, c) caused by large faults (violet arrows). Resolution of the obtained velocity is dense in both the lateral and vertical directions, allowing for a good match with well sonic information (d).*

To honour WAZ acquisition configurations, we used a cross-spread design with orthogonal source and receiver lines, as illustrated in Figure 3. To ease the operations, the source line used existing roads when possible, which explains the difference of regularity between source and receiver lines. For practical and economic reasons, the inter-receiver and inter-source distances were not dense enough to record the slow surface waves without aliasing. This acquisition was handled later during the data processing using data reconstruction by low-rank based inversion (Sternfels et al., 2016). Surface obstacles like cities or forests prevent a perfect shooting pattern; this also creates the need for 5D data reconstruction using anti-leakage Fourier transform. During the imaging phase, we used least-squares migration to further attenuate the acquisition pattern; LSM allowed the complex faulted reflectivity to be revealed (Salaun et al 2020).

Despite a careful survey design, operational constraints often add complications to the data processing task. For example, along with the relatively sparse design, acquisition was done during harvest season which necessitated a size reduction of the receiver array. With reduced receiver spacing, the reduced array had the benefit of acting as an acquisition filter by reducing the energy of the surface wave. By stacking several geophones of the receiver array, the laterally propagating surface waves were attenuated whilst the vertical waves (reflection waves) were reinforced. This acquisition problem had to be compensated with careful work on surface wave modelling via a data-driven interferometry method (Chiffot et al., 2017).

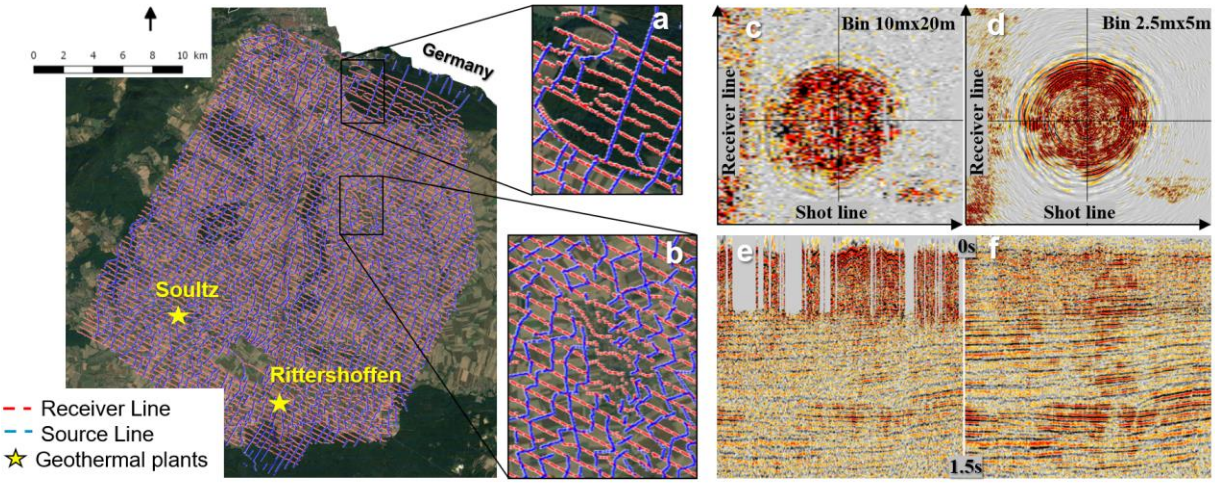

***Figure 3** 2019 acquisition map shows a sparser area when crossing a forest (a) or city (b). In addition, dense sampling is operationally expensive, as such, the chosen source and receiver intervals tended to alias the recorded surface waves (c). We performed Trace regularization and densification before removing surface wave energy (d). On the stack section, visible holes (e) are filled by the 5D interpolation and S/N is reinforced (f).*

From seismic imaging to interpretation

Careful consideration of both acquisition design and the data processing capabilities during the survey design provided a final seismic image that matched initial expectations. The new seismic volume fully images the top of the granite and the multiple faults underneath. Based on this data, geological interpretation was done by first picking the various horizons (Figure 4). This method is efficient when picking continuous reflectors, but it is more difficult to pick faults. Indeed, most of the faults are not actual reflectors but are often a simple discontinuity between two geological layers and so do not create a strong impedance contrast. In order to aid the fault interpretation and picking, an advanced fault enhancement (AFE) (Dorn., 2019) process has been done. This process is based on a 3D coherence estimation of the seismic cube. The use of this AFE volume greatly assisted the fault picking and, through the combination of horizon and fault information, we built a structural model. This model integrates the current wells and will greatly ease with the implementation of new production wells. With this detailed structural model, well-tracks can be accurately planned, and a single surface platform can be used to drill many deviated wells, saving on drilling cost and the ground preparation.

Pre-stack data, containing information of amplitude variation with offset and azimuth, can be further used in a quantitative interpretation to extract key rock properties like porosity or volume of facies and can potentially estimate the permeability of the geothermal formation. This work, not yet started in the URG, can provide additional crucial information to enhance geothermal production.

Conclusion

Geothermal prospects can have various geological targets from flat sedimentary layers, to deep complex faulting, or even structured basaltic formations. Using seismic prospecting to image these different targets will require specific acquisition designs. Often, an optimal survey design is not affordable, and trade-offs are required to ensure both sufficient seismic image quality and economic viability. By including processing and imaging information during the survey design planning phase allows for some acquisition parameters to be adapted for efficiency without damaging the final imaging result. In this paper, we showed how seismic acquisition can be designed whilst considering the sub-surface target to be imaged, the surface constraints, and the data processing capability. By combining this information, we shot a dedicated seismic survey in the French URG and the final obtained image fully met expectations. After interpretation of the seismic cube, we built a structural model aiming to assist with the implementation of future production wells.

This beneficial practice of survey design, achieved while considering the imaging technology which could be used in processing, can be applied for various subsurface applications either for imaging or for monitoring.

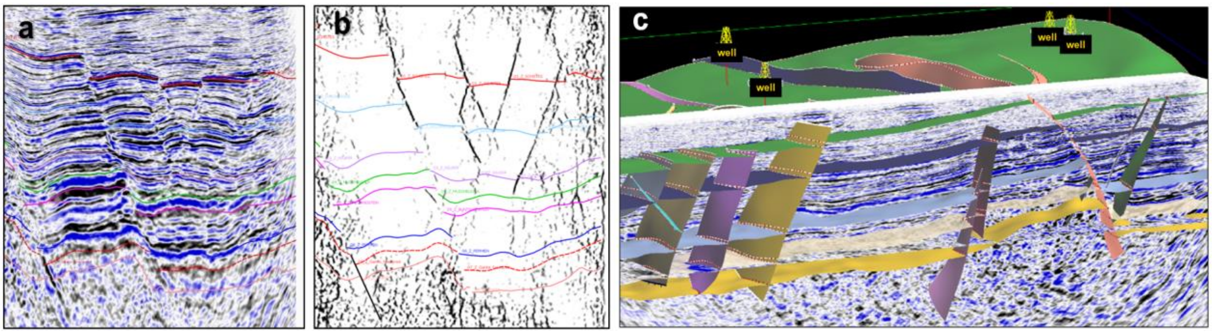

Figure 4 *Final seismic image (a) can be used to interpret the various geological events. Using advanced fault enhancement (b) faults can be easily picked to build a structural model (c). This model helps the understanding of the geological context and eases implementation of future wells.*

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