

Contribution of structural interpretation and CNN based quantitative interpretation to push boundaries of reservoir characterisation for deep geothermal development in the Paris region

Introduction

In a region with the highest concentration of geothermal plants in Europe and a production of 2 TWh in 2023, doubling or more the energy production from all renewable sources and reducing carbon emissions by 2030 are the priorities. The development of deep geothermal resources is critical to achieve national and regional energy policy ambitions. However, the number of installations in the western part of the region remains currently low, largely due to limited underground knowledge and the perceived less favourable conditions for geothermal resources development in comparison to the well-known and developed eastern and northern areas.

To address this, the ADEME agency, the Île-de-France Region and the BRGM have launched a deep geothermal exploration campaign in southern and western Paris: the GEOSCAN campaign. This program involves the reprocessing of vintage seismic and well data along with the acquisition of state-of-the-art 2D seismic survey, CSEM data and petrophysical measurements to improve subsurface understanding. This campaign will provide new imaging of the subsurface a reliable geological 3D model, and reservoir interpretations over the different aquifers ranging from 500 meters down to the basement, below 2500 meters depth. It will set a favourable framework for the development of additional geothermal infrastructures and help meet the targets of renewable heat production.

Dataset and methodology

A large dataset of existing vintage seismic reflection data, geothermal wells and hydrocarbon wells, has been collected across the region, mainly from oil and gas exploration in the 1960s and 1980s (cf. Fig 1.A). This dataset provides a good coverage over the area of interest allowing a relatively dense spatial sampling for structural interpretation, which is usually the standard in the geothermal industry. Allo et al. (2021) showed that despite the limited quality of the vintage seismic data in terms of frequency content and resolution (ranging between 15 Hz and 70 Hz in average), a quantitative interpretation provides additional information of the reservoir properties. Consequently, for the GEOSCAN research project, amplitude preserving reprocessing has been carried out over 1660 km of 2D vintage seismic reflection in the zone of interest to enable quantitative interpretation of the dataset. This reprocessing has never been carried out at such scale and for geothermal exploration purposes in this region.

Seismic acquisition has progressed tremendously since the 1980s in terms of spatial sampling and frequency content allowed. These advances, and in particular the ability to acquire broadband data (Baeten et al 2010) have a positive impact on impedance inversion (ten Kroode, 2013). For these reasons and to better understand the geothermal reservoir in area lacking information, the programme included the acquisition of 280 km of state-of-the-art 2D seismic data (Fig 1.A).

The new seismic reflection lines (Maurel et al., 2024) were acquired with a broadband frequency sweep of 48 s ranging from 2 Hz to 96 Hz to further improve quantitative interpretation processes. The receivers are wireless accelerometers spaced 20 meters apart. The source is a single vibrator with a maximum output of 65 000 lbs with an interval of 10 m. The use of random sweep allowed the acquisition of a given line with three vibrators and limited disturbances in densely populated area. The acquisition took place at night, which drastically reduced the recorded noise.

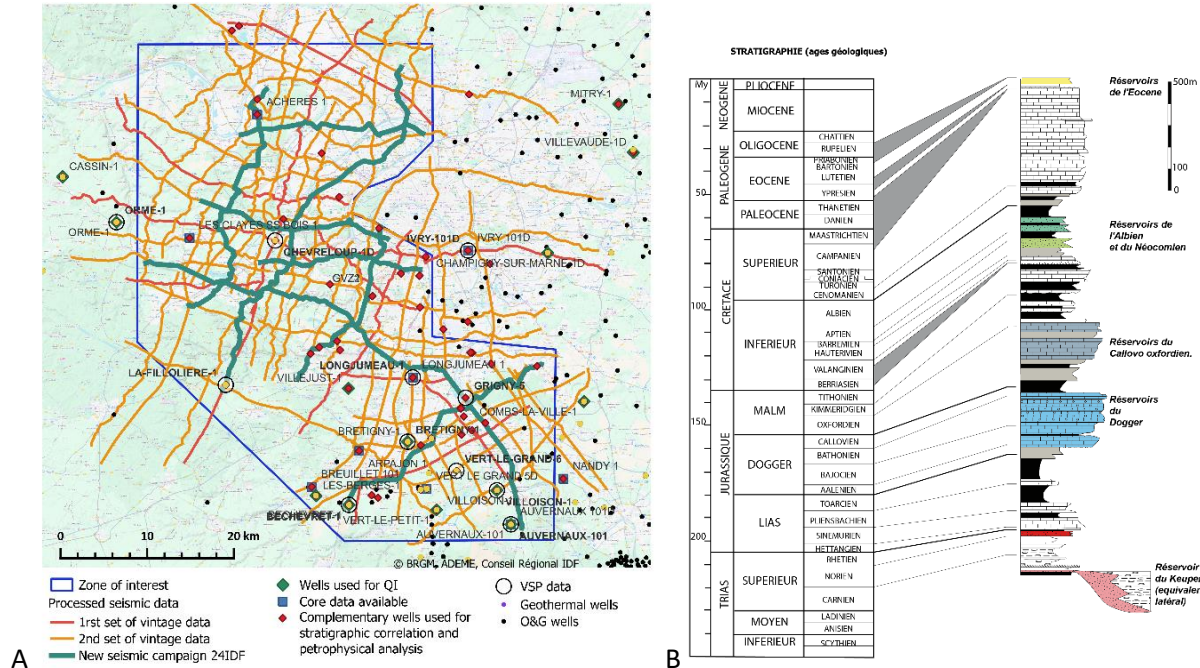


Figure 1. Map of the Geoscan Ile-de-France project perimeter with indication of vintage seismic lines and new seismic acquisition available (A) and summary stratigraphy of the Paris sedimentary basin (B) from BRGM and Guillaucheu et al. (2000)

Quantitative interpretation of seismic data

Both vintage and new 2D seismic datasets, along with well logs from 10 wells, were used to predict petrophysical properties (total porosity, clay volume and effective porosity) along the 2D seismic lines. A rock physics-guided machine learning approach (Downton et al., 2020), enabling direct prediction of target properties with associated uncertainty estimation, was applied. The workflow comprises two major steps: augmentation of the training data (synthetic catalogue generation) and neural network training and application. Synthetic catalogue generation involves rock physics model creation, statistical analysis, and scenario modelling to account for expected property and thickness variation at the zone of interest. Given the complex geological settings, which include a mixture of carbonate and clastic formations, different rock physics models were developed and calibrated for various facies. These calibrated models, combined with statistical analysis (mean and variance for each lithological layer), were used to model scenarios by varying the thickness and petrophysical properties of the target layers. 7 of the 10 wells studied were used for transfer learning while the 3 remaining wells were used for blind test. Hundreds of pseudo-wells were simulated, and synthetic seismic gathers were generated for each well, forming the synthetic catalogue.

Convolutional neural networks were subsequently trained on the synthetic catalogue to predict total porosity and clay volume. A transfer learning step was subsequently applied to incorporate the effects of real seismic data, thereby enhancing the prediction results. Finally, the permeability was calculated from the total porosity and clay volume. Different empirical relationships between porosity and permeability, tailored to different layers, were applied using core data measurements over the zone for calibration. The result of the petrophysical properties prediction for one of the 2D lines is shown in the Fig 2. The Oxfordian reservoir has been found to display high porosity values in this north-west area, with a progradation towards the East, accompanied by a thickening and deepening of the reservoir towards the east also.

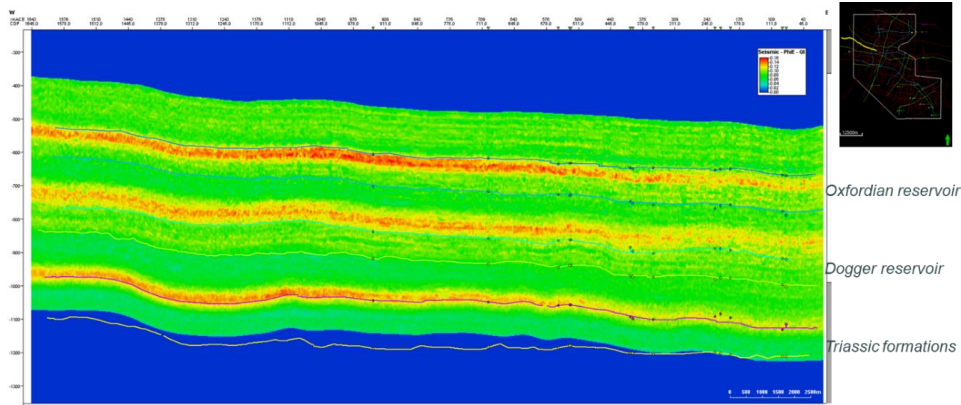


Figure 2. Effective porosity results over line 88PL-002, in the north-west of the zone of interest

The analysis of the quantitative interpretation results over the dense 2D seismic network provides better understanding and control of the reservoirs architecture and give a better constrain of reservoir geology. Given example, for the Oxfordian reservoirs, quantitative interpretation indicates an important porosity distribution from west to east along a topographic high, letting us to interpret a facies variation from a potential inner to outer domain. This specific new data strongly improves geological interpretation and, thanks to legacy data, will give a better constrain during the static reservoir modelling.

A complementary petrophysical and rock physic analysis was conducted over 19 additional wells in the zone of interest to complete the understanding of facies distribution and predict properties in the different reservoirs as well as to have a better control in the following steps of reservoir modeling. Results of quantitative interpretation of seismic data show a good correlation with petrophysical interpretation at these wells, away from the control wells used during CNN process, allowing a good confidence in the interpretation of lateral and vertical relative variations of the porous medium and connectivity within each reservoir.

Structural and petrophysical modeling

A detailed 3D velocity model was built to propose a thorough time to depth conversion workflow to convert post stack results as well as quantitative interpretation and proceed with structural modelling. Checkshot survey and valid Sonic logs were used for the construction of the model along with available 2D migration velocity profiles of 1900 km of seismic lines which were upscaled to create an average seismic velocity interpolated into a 3D grid using simple kriging. To compensate the deviation of seismic velocity in the grid compared to the well velocities, a scaling factor function was created between the two values and applied to the grid to adjust well calibration. The structural depth uncertainty was assessed using scenarios build from the base case velocity model and a normal distributed error with standard deviation of the velocity of 20 m/s.

The general seismic interpretation in time, when combined with a time-depth conversion, facilitates the proper delineation of reservoirs geometries and reveals a new detailed structural map of the area of Interest (Fig 3). A total of 19 faults have been identified over the zone. These structures influence deepest reservoirs, especially the Triassic and the Dogger formations. These faults exhibit a small offset in the various horizons and are mostly accentuated by anticline structures visible along these structures. The analysis of depths and thickness maps indicates two significant observations. Firstly, the occurrence of approximately 15 anticlines or fold structures and secondly, those structure exert a substantial influence on the thickness distribution of reservoirs. As demonstrated by the following example, the interpretations along the processed vintage and new seismic data have led us to provide a detailed description of the architecture of the Oxfordian reservoir along the well-known Beynes-Meudon anticline structure. Along this west-east oriented structures, which is flanked to the northern part by the fault of the same name, a marked variation can be observed from west to east. Indeed, the anticlinal structure is initially pinched in the western part of the study area, then gradually fades out towards the

east (Fig 2. and 3.). Further to the east, this structure is succeeded by new features, such as faults and antiforms, which have offset toward the north and are perceptible mainly in the Dogger and Triassic reservoirs. This level of details has never been attained before this scientific program.

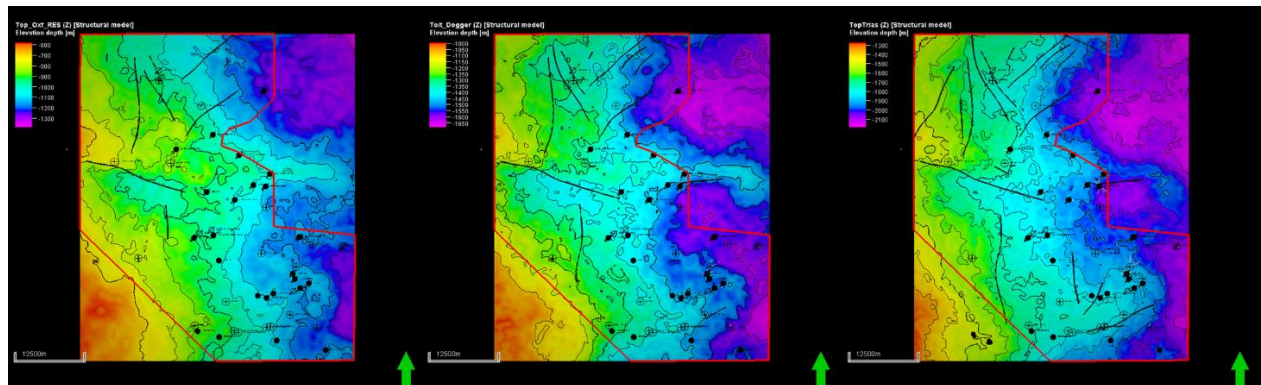


Figure 3. Structural maps of top Oxfordian reservoir (left), top Dogger reservoir (middle) and top Triassic reservoir (right) in depth and faults interception of each surface

Following the creation of the 3D structural model, a reservoir property model can be defined. The purpose of this model is to assess the geothermal potential in the zone of interest and provide valuable information and knowledge for project developers.

Conclusions

The analysis and interpretation of this substantial dataset of geophysical and well measurements over an area of 2000 km² has provided a new insight on the petrophysical distribution and structural schematics. This campaign led to an improvement of the geological understanding of this, heretofore, relatively unexplored area for geothermal development. The Geoscan program continues until the end of 2025 and preliminary results reveal the position and extent of reservoirs that could prove to be favourable for future geothermal wells in the area, especially the Oxfordian, not yet developed for geothermal heat production in the region. The program should help decision-making, minimize exploration costs, and promote sustainable geothermal resource development in the South and West of the Ile-de-France region.

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