# Geological investigations for CO2 storage: From seismic and well data to 3D modeling

Flavie Chapuis, Hugues Bauer, Sandrine Grataloup, Aurélien Leynet, Bernard Bourgine, Claire Castagnac, S. Fillacier, A. Lecomte, Y. Le Gallo, Didier Bonijoly

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 4 (2011) 4591–4598

Energy Procedia

www.elsevier.com/locate/procedia

GHGT-10

# Geological investigations for $CO_2$ storage: from seismic and well data to 3D modeling

F.Chapuis[a], H.Bauer[a], S. Grataloup[a], A.Leynet, B.Bourgine[a], C. Castagnac[a], S. Fillacier[b], A. Lecomte[b], Y. Le Gallo[b], D. Bonijoly[a]

[a]*BRGM, 3 av Claude Guillemin, 45060 Orléans Cedex 2, France*
[b]*Geogreen, 7, rue E. et A. Peugeot, 92563 Rueil-Malmaison Cedex, France*

**Abstract**

This work is part of the CPER Artenay project that aims at quantifying the environmental benefits and the technico-economic feasibility of storing $CO_2$ issued from a bio-ethanol distillery into a deep saline aquifer in the Paris Basin, France. This communication focuses on the geological investigations that ultimately lead to defining an optimal location for an injection site in Carbon Capture and Storage (CCS) project. This paper presents a new approach for the pre-site characterization going from seismic and well data analyses to storage design. First, the general context of the area has been set follow by seismic interpretation. Those investigations leads to a geological surfaces modeling taking into account the basin border location of the project. The next step is the properties modeling made using sequence stratigraphy surfaces and *Petrel* software. This work will conduct to choose the optimal injection location regarding this geological investigation and the environmental constrains.



Keywords: $CO_2$ storage; Paris basin; Aquifers.

## 1. Introduction

Geological investigation for $CO_2$ storage is usually set in the middle or deepest part of sedimentary basins. However, $CO_2$ producers do not always match with the geological settings, and so other geological configurations have to be studied. The Artenay project gives the opportunity to address this issue.
The study area is located near the South-West border of the Paris Basin, in the Orléans region (Fig 1). Particular geometry such as onlaping and pinching out of geological formation against the basement are likely to be observed. This paper focuses on the methodology applied with regards to this special geological context.

The workflow involves 4 main steps. The first step is a data review followed by a seismic interpretation and wells data analysis. Then, a 2D-model is computed, taking into account special geometries in relation with the geological setting. Afterward, a sequence stratigraphy and petrophysical analysis is undertaken. The last step is to build a 3D static model integrating all the previous results. This 3D model is ultimately used to compute a flow simulation. In due course, the results of such simulations will help to quantify the risk assessment of the modelled geological storage.

doi:10.1016/j.egypro.2011.02.418

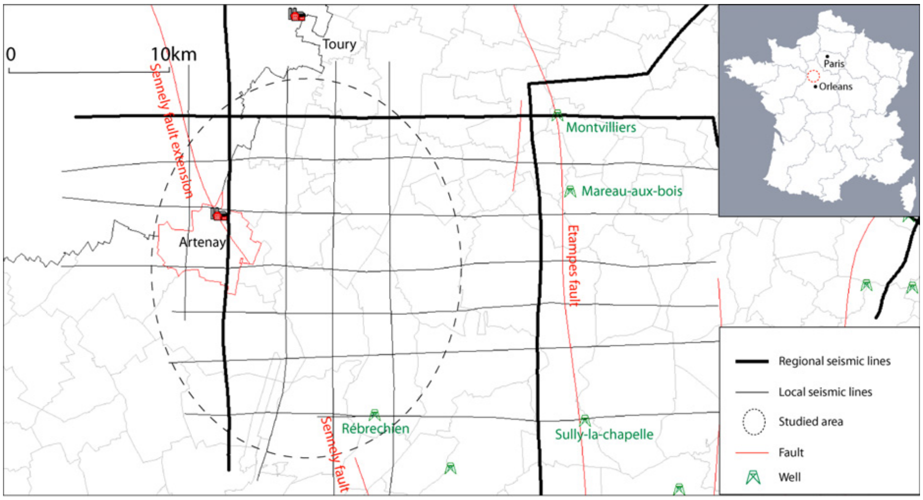


Fig 1 : Location map of the studied area.

Two deep saline aquifers are potentially good candidates for $CO_2$ storage, the Triassic continental deposits and the Dogger carbonates deposits. But both are known to have heterogeneous reservoir properties. From a previous study, salinity and temperature of each aquifer are known to vary linearly with depth at the scale of the study. The Triassic aquifer is highly saline and the Dogger is composed of mixed meteoric and marine waters.

The Triassic aquifer contains two main fluvial sand bodies, the "Grès de Donnemarie" Formation and the "Grès de Chaunoy" Formation. The overall is capped by the Upper Triassic/Lower Jurassic continental shales and Pliensbachian and Toarcian marine shales, which ensures a well containment. The Dogger aquifer is comprised of bioclastic and oolithic limestones which are a part of a shallow water carbonate platform that covered all the Paris Basin during the Middle Jurassic. Its cap rock is the Callovian and Oxfordian shales.

Two normal faults, with its extension, are identified the Etampes fault and the Sennely fault.

## 2. General Geological setting

### *2.1. Overall Geological setting*

The Paris Basin (*s.l.*) extends from the London basin, the North Sea, the Channel and its Atlantic margin to the Hercynian basement edges (Massif central, Massif armoricain, Ardennes, Vosges…). It is filled with up to 3000 m of sediments that corresponds to a 250 myr-long sedimentary cycle. First, a transgressive phase took place from the Permian lakes to the Jurassic carbonate platforms, and then a regressive phase started from the Cretaceous with the development of continental environments which have permanently settled since the Oligocene [1]. This long-term trend matches the tectonic history of the basin. An extensional context in relation with the rifting phase of the Tethys Ocean created normal faults in the Permian that remained active during the Jurassic. A first compressional (uplift) phase occurred during the Early Cretaceous, but subsidence of the basin got over it during the Late Cretaceous. The Tertiary tectonics was mainly compressional in relation with the Pyrenean and Alpine phases although a brief extensional episode set during the Oligocene. The Tertiary geodynamics of the Paris Basin is at the origin of its present-day structure [2].

The main lithologies found in the formations of the Paris Basin comprise alternation of sandstone, limestone and shale. The Triassic corresponds to sandstones and shales, the Jurassic is mainly composed of limestones and shales, the Lower Cretaceous is mainly made of sandstones, the Upper Cretaceous contains chalk and the Tertiary shows sands, shales and limestones, but it only appears in the south and the center of the basin.

Among the various aquifers that geologists listed, two were selected because of their large extension, salinity (i.e. not suitable for alimentary nor agriculture use) and depth (over 800 to 3000 m) that ensure the feasibility of $CO_2$ storage under supercritical ($P>73.9$ bar and $T>31.1$°C) state, a necessary condition for deep geological storage [3].

The Dogger (Middle Jurassic) aquifer is made of oolitic limestone and the Keuper (Upper Triassic) aquifer is made of sandstones. In a reservoir study, the cap rocks (cover) are of primary interest in order to avoid upward leakage. This role is played by the Lower Jurassic shales and the Upper Jurassic marls which both have a high porosity and very low permeability.

### *2.2. Stratigraphy of the aquifers and their cover*

The stratigraphic data used in this preliminary study come from three wells located in the studied area (Rébrechien, Montvilliers and Sully-la-Chapelle; Fig 1). The Triassic aquifers comprises two main sandy bodies (alluvial fan deposits), the 'Grès de Donnemarie' Formation and the 'Grès de Chaunoy' Formation. These are made of sandstone, dolomite and/or shale with, sometimes, dolomite in the upper part. The Triassic aquifers are capped by the Upper Triassic/Lower Jurassic continental shales. Eventually, the real cover is represented by the shales of the Pliensbachian and Toarcian.

The Triassic sandstones contain a regional saline aquifer going from Berry to Brie with an average salinity of 35g/l, a temperature of 74°C and an iron rate of 36 mg/l (from Melleray geothermic well located at 18 km south of Artenay).

In the studied area, the Dogger shows different lithologies on both side of the Sennely fault (Fig 2). Bioclastic and oolitic limestones with marls at bottom composed the western part. The eastern side is filled with limestone overcome by a high thickness of marls, oolitic limestone and finally a layer of marls. The overall is recovered by shale and shaly limestone with high amount of bioclasts, in the western part and by marls in the eastern side. The Dogger aquifer is composed of a mixed of marine and meteoric water; estimated temperature and salinity are 53°C and 20 g/l. The Dogger aquifer is capped by the Upper Jurassic deposits, composed of marls and marly limestones with a high difference of thickness between each side of the Sennely fault.

The Triassic and Dogger aquifers seem to have quite good reservoir properties. The 'Grès de Chaunoy' Fm has a high porosity and permeability as well as the Dogger oolitic limestone. More precisely, the Triassic has a primary porosity whereas the Dogger aquifer has a fracture porosity that enhances the primary porosity of oolitic limestones. The aquifers geometry is very different from one to the other. The Triassic sandstones are made of connected sandy bodies (lenses) including some shales, and lateral shifts of facies are very common (continental sediments); comparatively, the oolitic and bioclastic limestones are much more continuous sedimentary body, but at the scale of our study, the presence of shales /shaly limestone to the East has to be taken into account in the choice of the injection site. Moreover, heterogeneous cementation of the oolitic limestones will have to be considered for a suitable geological model.

## 3. Method

### *3.1. Seismic interpretation*

The Paris Basin has inherited faults from the Hercynian (Variscan) orogeny, which were reactivated during the Triassic and the Jurassic in an extensional context. Three groups of faults can be distinguished, according to their main direction [4]. The major group one with a N-S direction divides the south of Paris Basin into three structural blocks, the Armorican, the Biturige and the Bourguignon blocks, from West to East. The Sennely and Sully-sur-Loire faults belong to this group, the first one being the limit between the Armorican and the Biturige blocks. A second group is the Armorican fault system, with major trends NW-SE to WNW-ESE. It affects the basement with blocks tilted northward. The third group concern SW-NE faults; it is restricted to the very south and has a lesser effect on the sedimentary geometry. All these faults were active during the Triassic and Jurassic times, causing large heterogeneities in thickness from one tilted block to another.

From this background information, a seismic study has been done to characterize the geometry of these faults and to identify other ones. Results, reported in Fig 2, lead to the identification of three normal faults that cross the area among which the Etampes fault which affects all the formations from the basement to the lower Cretaceous. The Etampes fault has been reactivated during the Aptian (Early Cretaceous) with a reverse displacement and separates the western part from a more subsident area to the East where the thickness of deposits increases. The throw of this fault decreases towards the north and with depth. Concerning the two other faults (the Sennely fault and the Sennely fault extension), the throw decreases with depth. It clearly appears that the Etampes fault effect is more important than the Sennely effect.

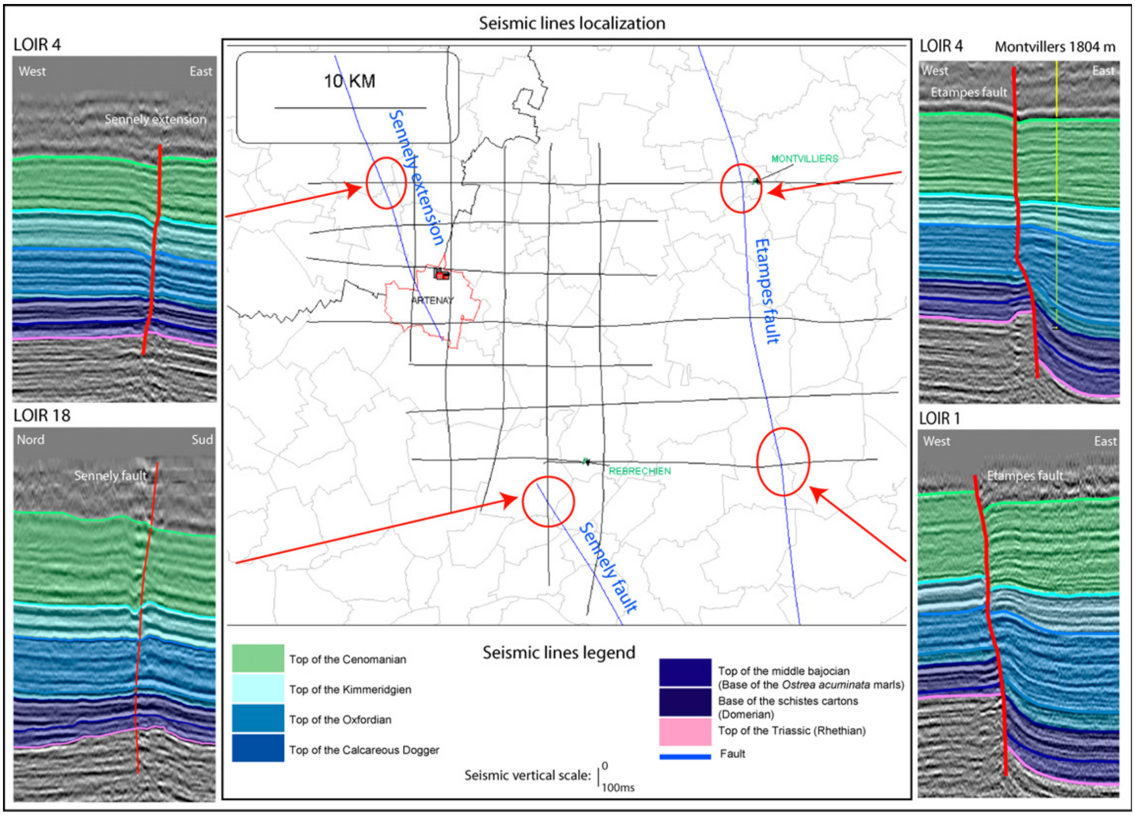


Fig 2 : Illustration of faulting activity during the Mesozoïc. Four seismic interpretations remarkably show the synsedimentary activity of faulting during Triassic (purplish and pinkish colours) and Jurassic (blue colours) times.

The general trend of the study area is a sub-horizontal geometry of the beds except close to the faults where bends (drag folds) can be observed. The beds gently dip towards East in consequence of the Etampes fault tilting; it is well shown by the isohypse map of the Kimmeridgian top (Upper Jurassic).

In conclusion, three main faults affecting the two reservoirs were identified and the general trend of the reflector is a deepening toward the East.

### *3.2. Structural modeling*

This step consists on building a 3D structural model of the 10 geological formations between the top of the calcareous Dogger and the base of the Triassic (Fig 3), using Isatis® and Petrel® softwares. The main difficulty is to generate a realistic model taking into account the special geometry linked to the basin border (onlap, pinch out…) and the faults affecting the target formation. The model involves the calculation of 11 surfaces (elevations of formation tops and/or bottoms). To do so, 3 types of information are combine 3 types of information:

- Existing 2D grids maps, at basin scale, for 2 of the 11 surfaces (Fig 3). Those grids are the result of older models for which initial data (such as seismlic lines) were not available. They are used as a constraint for the modeling.
- Well data (+/- 50 wells) giving elevation of top/bottom as well as thickness of each formation.
- New seismic interpretation (see previous section), for 3 of the 11 surfaces. One of the main results is a "new" fault network slightly different from the basin scale one. Only a small part of the model is covered by the seismic lines (Fig 4) which explain the used of basin scale map as a constraint.

The first step of the modelling is to update the fault system at a righter location. To do so, the new fault system deduced by the seismic interpretation is imported and replace on the basin scale map. Then, the area where different location for the same fault appears (up to 200m shift) is removed and the basin scale map is re-interpolate taking into account the new fault network. This method is used for the Triassic and Dogger surfaces.
In a second step these two surfaces are corrected in order to honor well data and new seismic interpretation. First, "modified" surfaces are computed by adding the difference between the basin scale surface and well data (using inverse distance interpolation of the difference). Then, the difference between those surfaces and seismic interpretation is interpolated by kriging. These corrections lead to the "final" surface for the tops of Dogger and Triassic (Fig 4).
The other intermediate surfaces are derived from the interpolation / extrapolation of thicknesses at wells, either as an absolute value for Triassic formations, and either as proportion for Dogger Formations.

According to the structural modeling, it appears that the top Triassic is outcropping on the west part of the studied area and the general deepening of the surfaces toward the east is verified. Regarding the Dogger, its top is less than 800 m deep in the West part of the studied area. This surface is too shallow, at this location, for injection of $CO_2$ at supercritical state. Consequently, the next part of the study focuses on the Triassic reservoir and integrates changes in petrophysical properties as a function of lateral lithological variation. This will lead to upgrade the model from 2D to 3D in order to perform the simulation of CO2 migration.

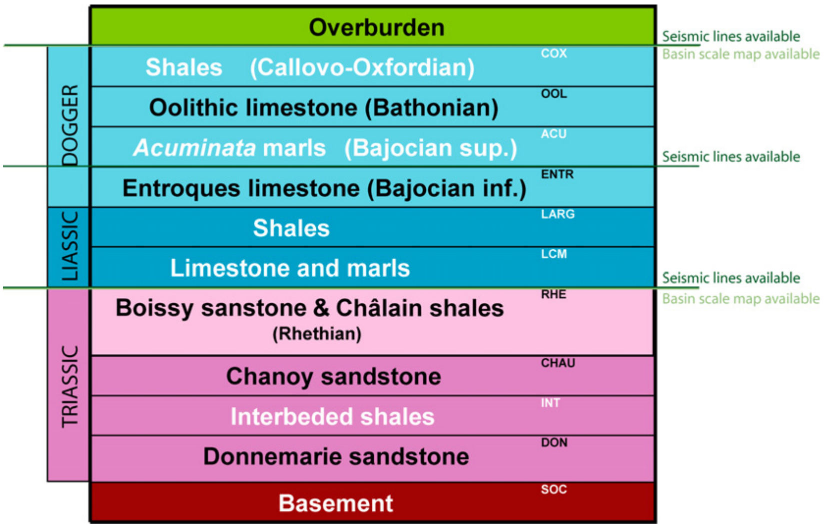


Fig 3 : Modeling surfaces.

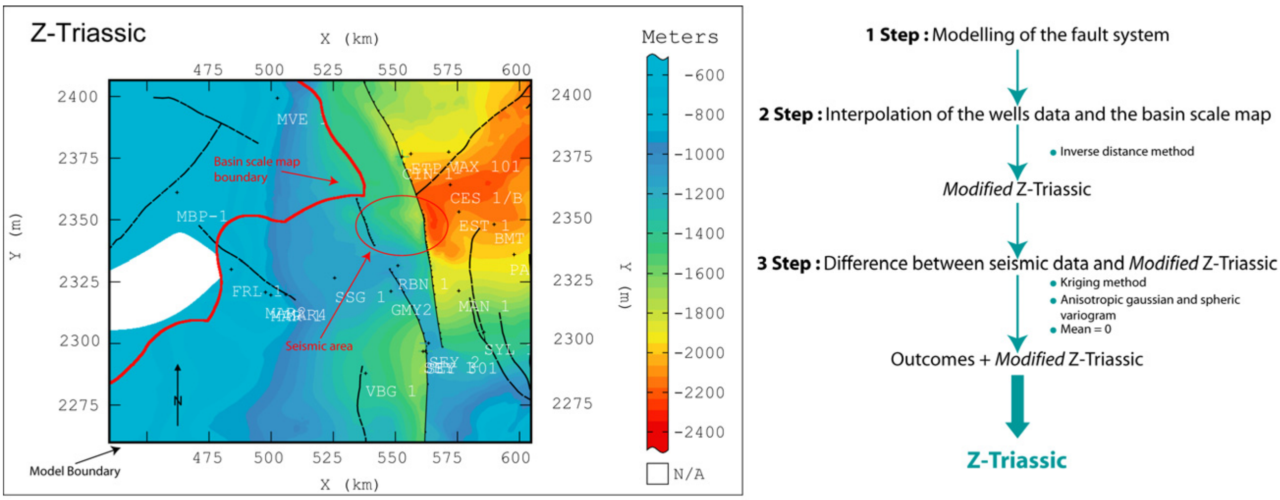


Fig 4 : Example of the Triassic modeling surfaces and associated modeling method.

### 3.3. The sequence stratigraphy

In order to perform the 3D modeling, we first apply sequence stratigraphy concepts on Triassic deposits in order to compensate the lack of quantitative petrophysical data in the Triassic. Three transects (Fig 5A), one E-W and two N-S (one in each part of the Etampes fault), are interpreted connecting a maximum number of wells and four genetic sequences have been correlated (Fig 5B). In the studied area, the Triassic is formed by the Chaunoy sandstones (fluvial Channel deposits), the interbeded shales (Coastal deposit) and the Donnemarie sandstone (fluvial deposits). Sandstone is the major deposit for the Chaunoy and the Donnemarie Formations (reservoir zone) whereas the interbeded shales are composed of anhydritic shales (seal zone).

The well to well correlation shows that the sediment supply direction is WSW-ENE [5] (Fig 5D). Coarser deposits are expected toward the West for the two reservoirs zones which is directly linked to the fluvial system orientation. Some local coarser deposits are present close to the faulting area (Etampes fault) and are likely to be linked to. Indeed, the fault activity might have cause a high which provides coarse element by subsequent erosion. Regarding the Chaunoy deposit environment, the reservoir facies are expected to be localized and in the preferential NS direction which is the main channel direction. The Etampes fault separates a subsiding area with thick deposit (up to 210 m) to the East from a thinner area to the West (up to 0 m in Melleray well). The Triassic deposits are onlapping against the basement to the west and consequently disappear in the extreme West of the survey area (Fig 5C).

According to this correlation, a percentage of shale has been calculated on each well between the correlated isochronous surfaces and will be used as heterogeneities property for the 3D modeling.

Finally, this study provides qualitative and quantitative data about the reservoir heterogeneities which are crucial for a realistic 3D-model. Paleoenvironmental reconstructions show that the sediment supply direction is WSW-ENE, implying more proximal deposits to the West, so better reservoir properties can be expected in that direction.

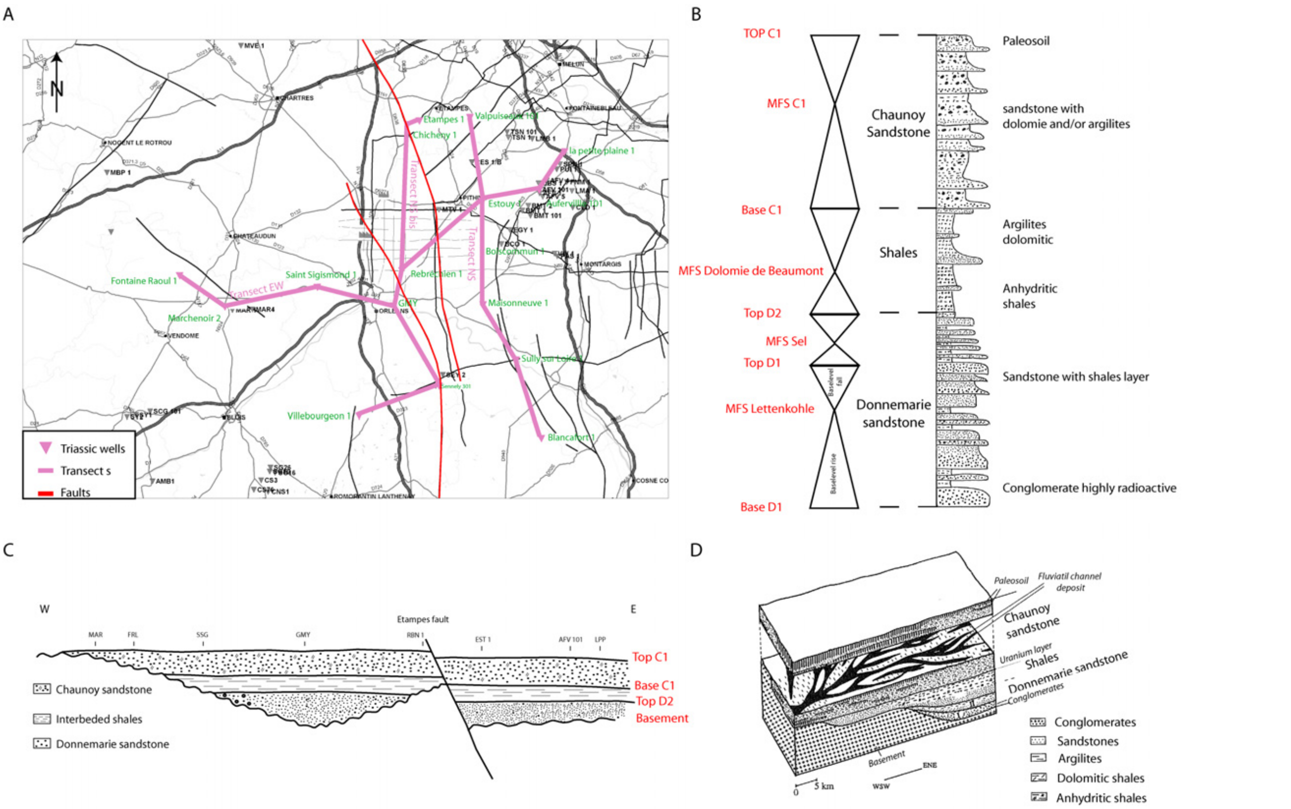


Fig 5 : (A) Transects location in the studied area. (B) Correlated genetic sequences [5, 6]. (C) EW cross-section of the studied area. (D) Paleoevironmental reconstruction [5].

### 3.4. The 3D modeling

The sequence stratigraphy study leads to a 3D static model including the 2D surfaces, the isochronous surfaces and the percentage of shale. The first step is to import the 2D surfaces, the faults, the wells and the associated percentage of shale and correlated isochronous surfaces. A more precise gridding is made focused on the sequence stratigraphy transects area. Then, the surfaces and the faults are re-interpolated (Fig 6).

The second step is to build a 3D gridding in order to perform the properties modeling. Four zones are defined and correspond to the Triassic formations (Rheatian, Chaunoy Fm, interbeded shales and Donnemarie sandstones). Then, a layering is made which corresponds to a more precise vertical gridding in the reservoir area and leads to the final 3D gridding.

The last step is to use geostatistical methods to estimate percentages of shale and sand in the 3D static model. In the sandstone formations, stochastic simulations are used to give 3D probability maps of those percentages. The core of the method is to define a variogram constrained, in that case, by the fluvial system parameters:

- The orientation of the anisotropy is equivalent from the South-West to the North-East sedimentary process;
- The ellipsoid of 3D constrains is equivalent to the size of the fluvial bodies (10km for the major axis, 4-5km for the semi-major axis and 10-50m for the minor axis).

In the shaly formations two methods are used, the first one is to assign a specific value and the other one is to calculate a moving average, which takes account of the values in a predefined neighborhood. With those methods, it is then possible to estimate the percentage of shale in the caprock layers with a small dataset (Fig 6).

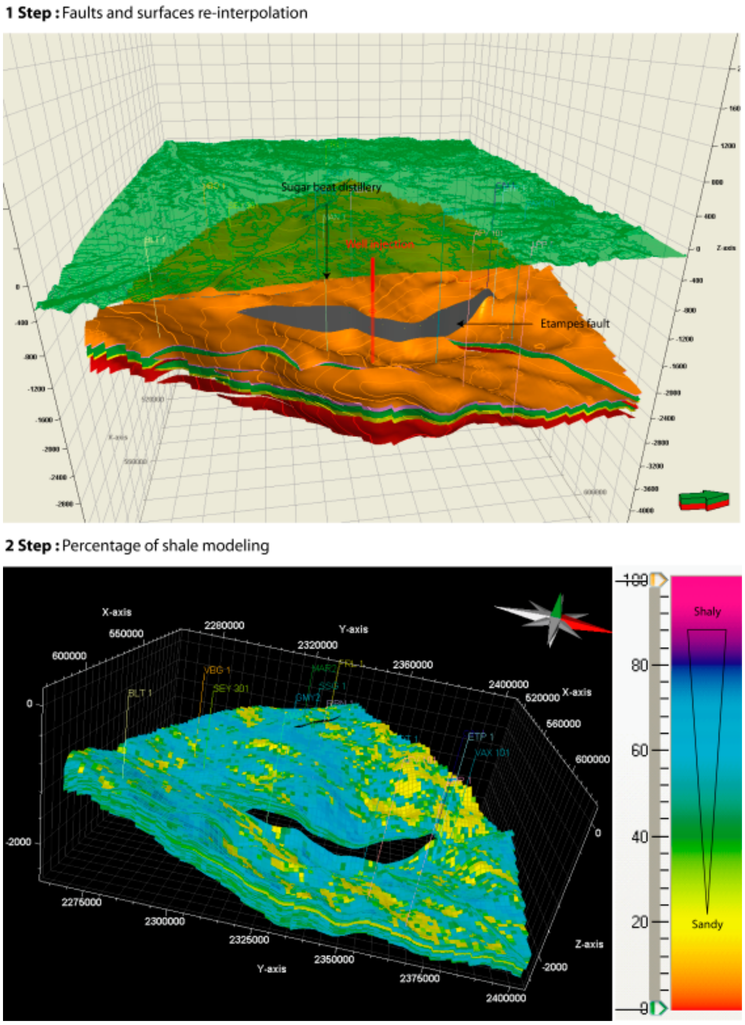


Fig 6 : The 3D modeling on *Petrel*.

Regarding the geological and geostatistical modeling results; it appears that the sandy deposits are localized in the west part of the study area which is consistent with the sequence stratigraphy result.

This static model will ultimately be used to choose the optimal injection location and to perform injection simulation. The goal is to estimate the injectivity and the extension of the overpressure within the aquifer and of the $CO_2$ plume after 30 years of injection. The results of these simulations will then be taken into account into the risk analysis of the project, which is of utmost importance to ensure safety and cope with public acceptance.

## 4. Conclusion

The purpose of this paper was to present the geological investigations that ultimately lead to defining an optimal location for an injection site in a Carbon Capture and Storage (CCS) project. This study reveals that the Dogger reservoir, in the study area, is not a good candidate for CCS due to its shallow depth in the west. Therefore, the sequence stratigraphy study is focusing on the Triassic reservoir properties and highlights the fluvial system orientation (WSW-ENE) and the associated deposits. Thanks to this geological survey, a 3D property modeling is performed and will be used for the injection simulation; the result will be taken into account in the risk analysis.

## Acknowledgement

The project is supported by the French Ministry of Research (DRRT), the regional Council “Région Centre”, the European Regional Development Fund (FEDER) and the BRGM.

## References

1. P.N. De Wever, F. Guillocheau, J.Y. Reynaud, E. Vennin, C. Robin, A. Cornée, D. Rouby, C.R. Palevol No 1 (2002) 399
2. J. Delma, P. Houel, R. Vially, Paris Basin, Petroleum potential. IFP report, France, 2002
3. ADEME, BRGM, IFP, $CO_2$ capture and storage in the subsurface. Geoscience Issues, France, 2007
4. JP. Gély, J. Lorenz, Geobios 39, (2006) 631-649.
5. S. Bourquin, C. Boehm, J. Clermonté, M. Durand, O. Serra, Bull. Soc. Géol. France. T. 164, n°2, (1993) pp 177-188.
6. V. Bouchot, A. Bialkowski , S. Lopez, A. Ossi , Avec la collaboration de JP. Chilès, C. Garibaldi, C. Jorand, Evaluation du potentiel géothermique des réservoirs clastiques du Trias du Bassin de Paris. Rapport final BRGM – RP–56463- FR, 92p, 40 fig., 3 tab., 1 ann, (2008)