Target area of Paris Basin Region - FR

Data inventory, seismic target and GAP analysis

Release Status: Final
Authors: F. M.L. Veloso; A. Estublier; D. Bonte; F. Mathurin; J. Frey; J. Maury; M. Poumadère; S. Stephant
Date: December 2021
Filename and Version: D2.1_PilotSTRATEGY_ParisBasin
Project ID Number: 101022664

PilotSTRATEGY (H2020- Topic LC-SC3-NZE-6-2020 - RIA)

Document History

Location

This document is stored in the following location:

Filename	D2.1_PilotSTRATEGY_ParisBasin
Location	

Revision History

This document has been through the following revisions:

Version No.	Revision Date	Filename/Location stored:	Brief Summary of Changes
Draft#1	18/10/2021		
Draft#2	15/11/2021		
Draft#3	27/11/2021		
Draft#4	10/12/2021		

Authorisation

This document requires the following approvals:

AUTHORISATION	Name	Signature	Date
WP Leader	Mark Wilkinson		20/12/21
Project Coordinator	Fernanda de Mesquita Lobo Veloso		20/12/21

Distribution

This document has been distributed to:

Name	Title	Version Issued	Date of Issue
		PUBLIC	00/00/0000

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

Veloso, F.M.L.; Estublier, A.; Bonte, D.; Mathurin, F.; Frey, J.; Maury, J.; Poumadère, M.; Stephant, S. 2021. Target area of Paris Basin Region – FR: Data inventory, seismic target and GAP analysis. EU H2020 PilotSTRATEGY project 101022664, report, pp 29.

Disclaimer

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

Executive summary

This report presents the CO_2 storage area in France to be fully characterised in PilotSTRATEGY and the target for the 3D seismic survey. This report also includes an inventory of available data in the selected area and a gap analysis.

The CCS concept linked to the pilot storage plant has been changed since the project proposal was submitted. Work in the STRATEGY CCUS project identified the opportunity to start the storage pilot by injecting CO2 already captured with a high level of purity from a fertilizer industry located in the Paris Basin region. Consequently, the option to change the target injection site was also considered.

Three geographical areas were screened to explore possibilities to optimize and reduce CO2 transport for the CCUS pilot concept linked to the storage plant. Two of the areas considered are being studied in CO2SERRE and the STRATEGY CCUS projects. A new area close to the emission source is also considered around Grandpuits. In all three possible areas both the Keuper and the Dogger formations would provide good reservoirs to store CO2 at the pilot scale, with a target of injecting up to 100 kt of CO2 under a Research Permit.

The new area investigated here, around Grandpuits, was chosen as the target for full characterisation including seismic surveying. This area is a promising region to engage in the decision-making of CCS technology deployment where the storage site is perceived to be a useful and beneficial technology for CO2-emission reduction to achieve the Paris agreement at regional/local level.

Despite of a lot of data available in the area or nearby of the selected area, some information should be acquired to the technical characterization of the storage complex. New data is planned to be acquired in the WP2 (Geo-characterization) for the characterization of reservoir and seal rocks and their interaction with CO_2-rich fluids. The new 3D seismic will allow to characterize geologival structures with a resolution of approximatively 30 meters. Outcrop studies could be useful to populated facies models, which have a resolution between seismic and core scales.

The selected area was studied in the past during the hydrocarbon exploration works. “Dry” wells were drilled the entirely Dogger Fm, their cementation and current casing quality should be investigated in detail, as these are the most likely leakage pathways. Further, the possibility to use these wellbores as monitor wells should be assessed.

The PilotSTRATEGY project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 101022664

Table of Contents

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

1. Introduction

PilotSTRATEGY aims to fully characterize geological sites and prepare legal and technical documents with the support and engagement of regional stakeholders in the deployment of a geological storage pilot plant of CO_2 in Deep Saline Aquifers located in three regions: the Lusitania Basin in Portugal; the Ebro Basin in Spain and the Paris Basin in France.

The Paris Basin in France is the largest onshore French sedimentary basin (Figure 1). First volumetric estimations of CO_2 storage capacity in the Paris Basin ranged from 800 Mt up to 27 Gt of CO_2 (GESTCO[1] and GeoCapacity[2] projects). Two sedimentary formations, the Dogger Fm of the Middle Jurassic and the Keuper Fm of the Triassic, present known and good reservoir levels in the Paris Basin area; the area being studied in STRATEGY CCUS (Veloso, 2021) (Figure 2).

The Dogger Fm is carbonate rocks (limestones) studied in GESTCO and Geocapacity projects and classified as Tiers1 resources (theoretical capacity) with a capacity of 4320 Mt (Storage Efficiency Factor [SEF]=6%) and 1440 Mt (SEF=2%). In these projects, the storage efficiency was 6% and 2% (conservative approach) and the density of CO_2 was 400 kg/m^3, which corresponds to an approximate depth of 1400 m and temperature of 70°C. The difference between the amounts estimated for the identified traps and the aquifer at large scale are huge, demonstrating the need for large structures in front of the CO_2 productions of the integrated plants.

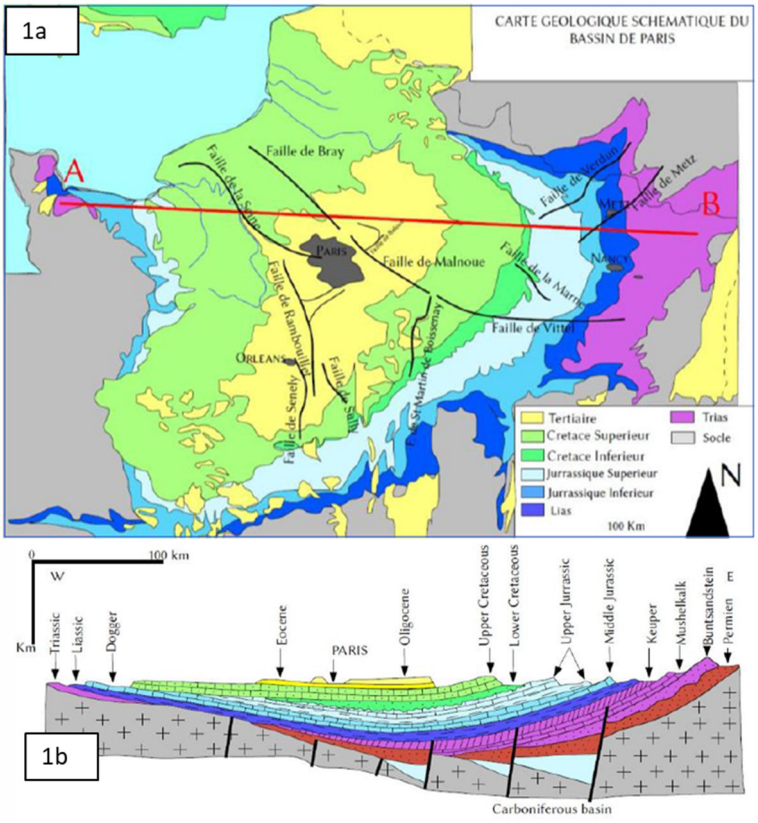

Figure 1: (1a) Geological Map of Paris Basin. A-B represents the cross-section in figure 1b

[1] https://cordis.europa.eu/project/id/ENK6-CT-1999-00010/fr
[2] https://cordis.europa.eu/project/id/518318/fr

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

The Keuper fm. includes the Donnemarie, Chaunoy and Boissy sedimentary members and is composed of silici-clastic sediments (Figure 2). The France Nord project (2013) carried out detailed modeling of Keuper fm. producing accurate assessments of the storage capacity by: refining geological and dynamic modeling, especially in the injection areas, testing several scenaria for commissioning of CO_2 injectors, and investigating the behavior of the CO_2 through time. Two areas of the Paris basin were evaluated for a storage in the Keuper Fm, one to the North of Paris town and another to the South of Paris. The capacity estimates for Keuper sud through dynamic modelling was 140 Mt of CO_2 for 40 years of injection; and for the Keuper Nord, it was 81 Mt of CO_2 for 40 years of injection. Storage capacities and injection well locations from studies of the France Nord project are used in STRATEGY CCUS project to elaborate economical-based CCUS scenarios (Coussy, 2021).

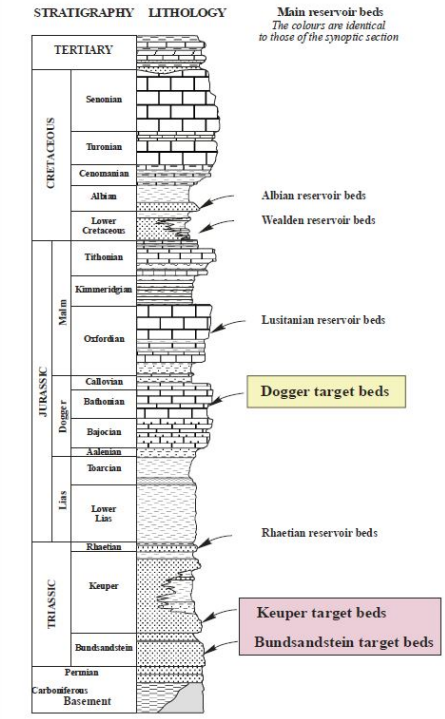

Figure 2: Schematic Stratigraphic and lithological column of the Paris Basin indicating the target reservoir studied in GESTCO, Geocapacity and France Nord projects.

1.1 CCS concept for PilotSTRATEGY

The awareness of CCS technology in the broader public continues to be rather limited and acceptance levels are found to be moderate on average. Social acceptance is partly influenced by the CO_2 source (Dütschke et al., 2019). Studies to assess the feasibility of a pilot storage plant of CO_2 should be linked to a potential CO_2 capture site at an industrial facility or power plant. The storage site should be perceived as useful and beneficial technology for CO_2-emission reduction to achieve the Paris agreement at regional/local level.

Adapting the identity of a project to local factors , such as the presence of industry, transport network, or benefit from the exploitation of underground resources , could support the responsiveness to local concerns. The choice of sites and how the technology is framed should played a key role in public opinion to projects. The Public's voices should be included early in the decision-making processes. Therefore, an evaluation of the suitability of potential locations that

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

builds on how local values can be supported by the technology opens up potential trajectories for future projects (Rothkirch & Ejderyan, 2021).

Through pilot projects, it is possible to show stakeholders that CCS is feasible and this is important for public perception and political support. Pilot projects, which are not of a sufficient scale to be considered as large-scale projects, provide valuable information to assist in the design and development of CCS projects and advance the understanding of the behaviour of CO_2 in the subsurface.

In the short term, CCS will provide opportunities to reduce the CO_2 emission of key industries in the economic development of the studied region and demonstrate the applicability of CCS for small-medium emitters at the pilot scale.

During the preparation of the PilotSTRATEGY proposal, the CCUS concept for the geological pilot in France was based on the CO2SERRE project. In the CO2SERRE project (Gravaud et al., 2021), the storage pilot plant should store CO_2 from a Biomass plant to implement a BECCUS pilot in the Orleans area. Up to 85 kt/y of CO_2 (IREP, 2018[3]) could be captured from a biomass cogeneration plant in Orleans, resulting in negative emissions. A small fraction of captured CO_2 would feed greenhouse crops around Orléans. The studied storage plant of CO2SERRE project is close to the emitter (< 20 km) and the geological target is the silici-clastic sediments of the Triassic Keuper Fm (Figure 2).

Today, the CCS concept being considered for the pilot plan in PilotSTRATEGY project has changed. The progress of work in STRATEGY CCUS[4] project helped to identify the opportunity to start the storage pilot by injecting CO_2 already captured with a high level of purity from a fertilizer industry located in the Paris Basin region, i.e.: Ile de France administrative region and Loiret department. In the production chain of nitrogen fertilizers, by far the biggest part of the CO_2 emissions comes from the Steam Methane Reforming (SMR), which is used to produce the Hydrogen required for Ammonia synthesis. Around 2/3 of these emissions are already captured. Part of this high purity CO_2 (99% on dry basis) is liquefied and sold to customers. The rest (more than 300 000 t/y) is vented to atmosphere.

2. Choice of the pilot site

Taking into account the very good potential of the Paris Basin in providing storage resources, a screening of three areas was made to explore possibilities to optimize and reduce CO_2 transport for the CCUS pilot concept linked to the storage plant. Two areas considered are being studied in CO2SERRE (data from Artenay project, Bonijoly et al., 2009) and STRATEGY CCUS (data from France Nord project) projects. A new area close to the emission source capturing CO_2 (Emitter ID: FR1.ES.002 in Figure 3) is considered around Grandpuits, where both reservoirs, the Keuper and the Dogger fms. would provide good candidates for a CCS pilot.

The three candidate zones selected (Figure 3):

- the Sologne area being studied in the CO2SERRE project close to Orléans town (green box).

[3] French Database of Pollutant from Industrial Installation (https://www.georisques.gouv.fr/donnees/bases-de-donnees/installations-industrielles-rejetant-des-polluants)
[4] https://www.strategyccus.eu/

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

- the area studied in France Nord project and being consider in STRATEGY CCUS plans to deploy CCUS in the Paris Basin region (Ile de France and Loiret departments) (yellow box);
- the area around FR1.ES.002 facility – PilotSTRATEGY new prospective area (brown box).

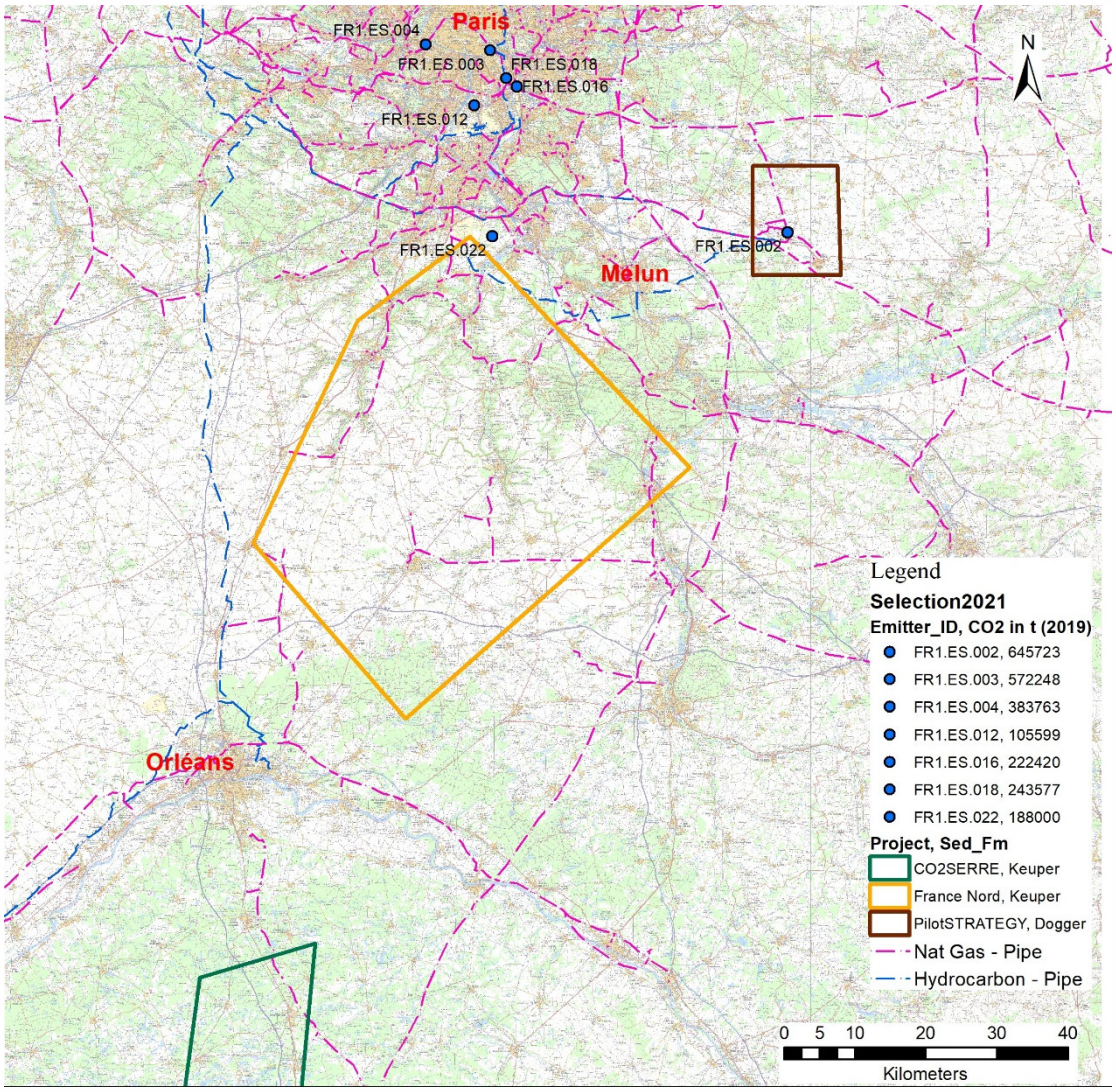

Figure 3: Preliminary selected areas from previous studies: CO2SERRE and France Nord; and the third proposed area here. Selected emitters in the project STRATEGY CCUS are indicated with their respective CO_2 emission in tons (IREP, 2019), as well existing gas natural and hydrocarbon pipelines.

2.1 Geological targets

2.1.1 Keuper formation – Trias

The Keuper Fm corresponds to a known reservoir for hydrocarbon resources composed of sandstones and conglomerates deposited in fluvial and deltaic geological settings. The strata can be very thick and are heterogeneous . Keuper reservoirs are sealed by anhydritic clays and Hettangian marls and shales up to 300m thick (Bonijoly, 2003). The Keuper Fm is considered in STRATEGY CCUS project as the best storage unit of French regions (Veloso, 2021).

The lower fluvial reservoir (Early Keuper - Donnemarie) consist of piedmont deposits with conglomeratic bed at the base grading up to finer grained sediments. It is relatively rhythmic with

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

sandstones at the top. Grain size of deposits decreases from the South to the North direction. The upper fluvial reservoir accumulated during the Late Keuper (Chaunoy sandstone) in two sub-basins: one in the South of the Loire river, the Sologne area (area investigated in CO2SERRE project), and the other in the Brie region (Figure 4).

The thickness of the deposit was controlled by the activity of deep basement faults, and in particular, the Sennely fault. The two subsiding basin formed principally during the deposition of the Upper fluvial reservoir correspond to two thicker zones:

- The Brie sub-basin with an accumulated thickness exceeding 300m (Donnemarie and Chaunoy sandstones). The top of the reservoir depth is located at 2500 m-deep in the area around emitter FR1.ES.002 (Figure 4).
- The Sologne sub-basin more than 400 m of accumulated thickness for both reservoirs. The top of reservoir is located at 1500 m-deep in the Sologne area (Figure 4).

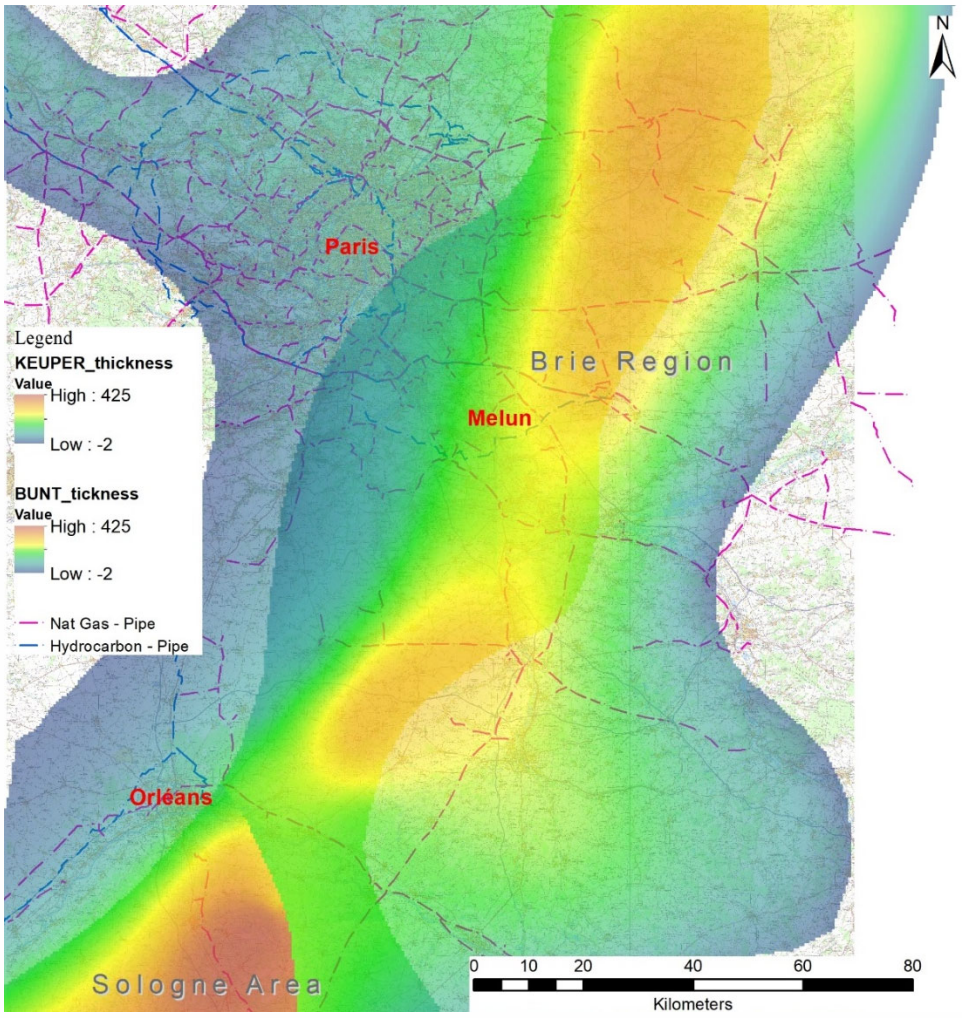

Figure 4: Thickness map of the Trias deposit represented by the Keuper fm. and Bundsandstein fm. (Geothermal Atlas, BRGM 2019).

2.1.2 Dogger formation – Jurassic

The Dogger reservoir has been an important oil-reservoir target since the 1950s. Currently, forty geothermal plants are in operation in the Paris region, supplying hot water and heat from the

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

Dogger aquifer to some 210 000 housing units. The Dogger aquifer has been supplying hot water for district heating networks since the 1970s. It is a very productive aquifer, with water extracted at a temperature of 55° to 85° from depths of 1500 to 2000 metres. But over time, the performance of some wells has been affected by corrosion and the deposition of scale, and by drops in productivity or cooling due to "cold bubbles" forming around the re-injection wells.

The Dogger Fm was formed on a carbonate-shelf system including an external open-sea domain and an internal restricted-marine domain. A high-energy depositional setting of barrier system and peripheral reef flats separate these domains. The external open-sea domain is a low-energy marine environment with marls, mudstones or mudstone with pellets. The fore-barrier reef flat corresponds to moderate to high energy deposits of grainstone and gravelly and bioclastic packstone. The barrier is a very high energy setting with bioclastic and oolitic grainstone. The back-barrier reef flat is a moderate to high energy environment composed of oolitic grainstone, wackestone with intraclasts, pellets, oncoliths and bioclasts. The lagoon is the low energy depositional setting with subtidal bioclastic wackestone-mudstone, wackestone, intertidal packstone with pellets, biopisoliths and bioclasts, supratidal wackestone-mudstone with algae, fenestrated and desiccation structures (Bonijoly, 2003).

Potential reservoirs are related to high-energy depositional settings of the barrier and surrounding reef flats. Oolitic grainstones of the barrier system deposited principally during the Bathonian (Figure 2) are the main reservoir target with a thickness up to 200 m. Although the *Dalles Nacrées* (Callovian – Upper Dogger) are fractured limestone target of the Charmotte oil-field in the South of the Grandpuits area, their potential for CO_2 storage is low, as they are thin (15-40 m-thick) and fractured. The seal rocks of the Dogger reservoirs are the low-energy open-marine deposits composed of marls and mudstones with 20-40 m of thickness.

2.2 Quick look of the prospective areas

The three selected areas (Figure 3) have different geological target reservoirs depending to their depth, thickness and lithology.

2.2.1 CO2SERRE - Sologne Area

This is the area being investigated in CO2SERRE project (Figure 3). The area is close to the heat-cogeneration plant in Orléans. In the selected area, no wells are available. Few wells are available in the Northern part of the area, close to the Orléans town. The Keuper Fm is the target reservoir and is found at 1500 m deep. The reservoir is good, although some problems of injectivity were found and solved using sand-screens for the well completions.

A nearby site was previous assessed in the CPER Artenay project supplying the geological model for the first estimation of storage capacity being made in the CO2SERRE project. The geological model and petrophysics distribution is based on regional data, so that the accuracy of the data is low.

The uncertainty of facies distribution and reservoir connectivity is high in this area. Besides, the area is not well connected to existing pipelines and it is more than 100 km from emitters identified in the STRATEGY CCUS project (Figure 3). In the North part of the area, existing gas pipelines could be useful to transport CO_2. The feasibility to constructing new pipelines close to existing ones, and the re-use of old ones to transport CO_2 should be assessed.

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

2.2.2 France Nord project area

The Keuper Fm is the target reservoir of the area. A detailed modeling of Keuper Sud site resulted in an assessments of the storage capacity as Tier 2 (effective capacity) by: refining geological and dynamic modeling, especially in the injection areas, testing several scenaria for commissioning of CO_2 injectors, investigating the behavior of the CO_2 with time. The objective was to optimize the number of injection wells to reach 200Mt of injected CO_2 in the reservoir over 40 years.

Data and information were supplied by the France Nord partners. These data were reprocessed in 2010-2012, is scarce in the studied area and quite old. Further, the dissolution of CO_2 was calculated through an analytical solution as the numerical simulator was not able to solve thermo-dynamic laws to describe the behavior of the CO_2 though time.

Two different petrophysical models were built from core, logs and production tests in the selected area indicated in the Figure 3 as France Nord, Keuper:

- the first one includes porosity, from logs measurements, and permeability calculated using a Phi/K relationship.
- the second one includes a petrophysical facies modeling, based on a study done by Engie. Then, permeability and porosity were modeled for each facies, in order to have a more representative geographical distribution of the properties.
- Kv/Kh is 0.1.
- Reduction of the net thickness estimation for all layers. Very heterogeneous reservoir (fluvial deposits –horizontally and vertically unconnected channels).

Note that modeling water production did not improve significantly the capacity due to the challenging connectivity of the sandstones.

- The total of CO_2 injected in the petrophysical model without facies was 140 Mt (P50 or average case) during 40 years using 15 vertical injector wells
- Total injected CO_2 up to 54 Mt for 40 years of injection through 15 vertical wells (P50 or average case) for the case with a facies model.

The France Nord area was studied in detail and the capacity estimation has a better maturity and confidence than estimates in the other 2 areas. The simulation study in France Nord located some injector wells in the Northern part of the area, which could reduce transport distances from emitters identified in STRATEGY CCUS (Figure 3)

2.2.3 PilotSTRATEGY - new area

The area around the emitter is mostly rural with the land used for wheat crops (Figure 3),however oil and gas industry is present. Three licenses of hydrocarbon exploitation in the Keuper Fm. are being operated by Vermilion around the area and one license in the Dogger Fm exists in the southern side of the area (Figure 5). Although these hydrocarbon fields currently are operating, they shall stop their research and exploitation by 1st of January 2040 (French decree[5], 2017).

[5] https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000036339396

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

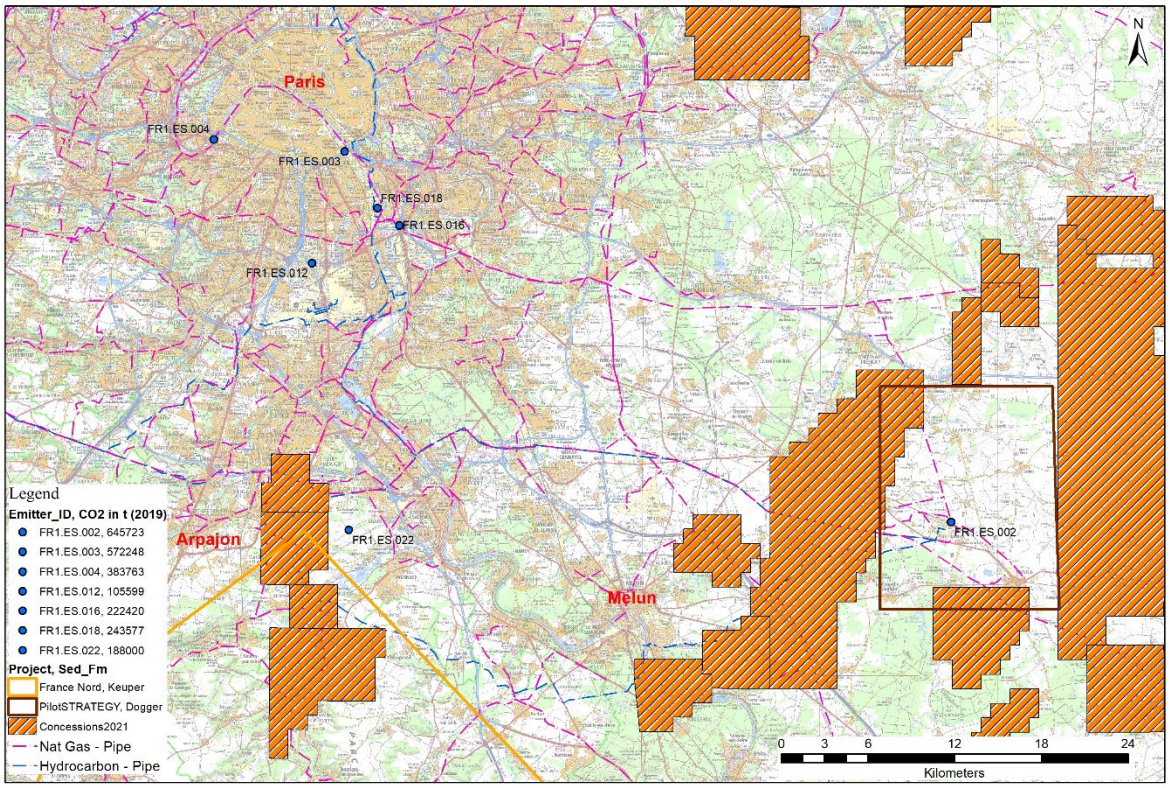

Figure 5: Current Hydrocarbon concession around Grandpuits facility.

The storage capacity in this location was not estimated yet as Tiers2 (effective capacity of the field). However, both reservoirs of the Dogger and Keuper formations are present and are known as good reservoirs (Figure 5).

As detailed in the previous section (2.1.1), The Keuper in this area is deeper and is currently an oil-field production in the boundaries of the selected area. Oil fields are likely compartmentalized by sedimentary heterogeneity linked to the fluvial system or by faults. Seven old-wellbores in the area reached the Keuper Fm with few cores available. Keuper reservoirs are more than 2500 m deep in this area (Figure 5).

The Dogger Fm is also known as good reservoir in the area. The top of the (Bathonian) Dogger reservoir around the emitter FR1.ES.002 is around 1700-1800 m-deep. The geothermal potential linked to the high permeability and porosity of the Bathonian (Middle Dogger) is well known around the Paris and Melun towns. Nine old-wellbores are available in the area and many cores were drilled close to the investigated area (Figure 6).

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

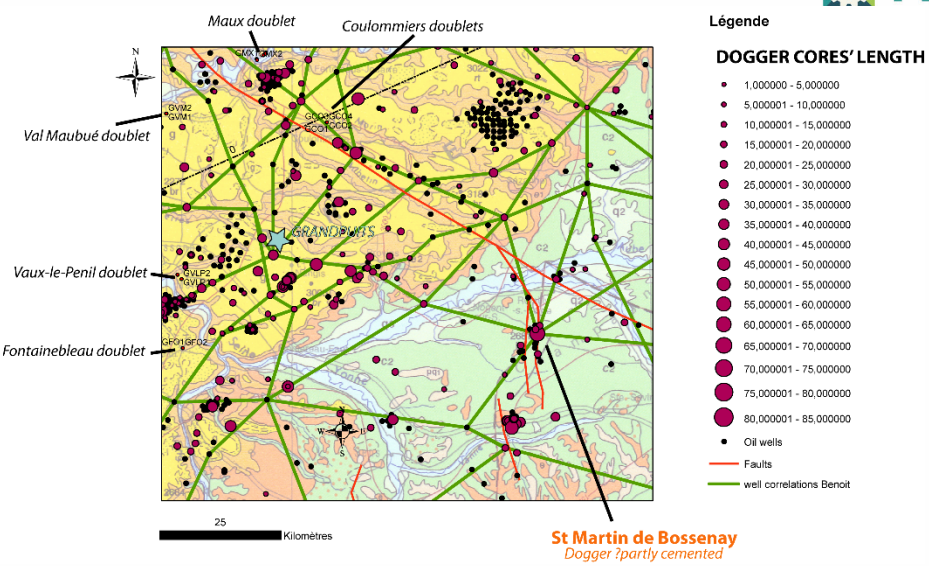

Figure 6: Accumulated core's length of the Dogger around Grandpuits area (blue star)

This zone is connected to oil pipelines, gas pipelines and have an important history of oil and gas production, as well transporting refined oil. A refinery in the area is being converted to industrial production of biofuels and bioplastic[6].

2.3 Seismic target – selected area

In the three preliminary selected areas in Figure 3, both the Keuper and the Dogger formations would provide good reservoir levels to store CO_2 at the pilot scale, which means to inject up to 100 kt of CO_2 under a Research Permit[7]. Other technical criteria should be also considered in choosing the area for the pilot. In order to enable the fast deployment of the CCS pilot in the Paris Basin, a capture project or a capture system should be in place by the end of the full site characterization, it means by the end of the project in 2026.

The new area investigated here, PilotSTRATEGY new area, was chosen as it seems a promising region to engage in the decision-making of CCS technology deployment. Storage projects proposed in industrial areas or close to industrial facilities were often more successful than the ones proposed in "natural" sceneries, as they did not disrupt the landscape and people were familiar with the risks (J. von Rothkirch & O. Ejderyan, 2021; e.g. Wolsink, 2007; Batel et al., 2015; Devine-Wright and Wiersma, 2020).

The presence of industrial facilities in the area to launch the pilot offers a possibility of planning a low cost CO_2 transport as the storage site would be close to the emission point. Existing infrastructures such as pipelines (natural gas and hydrocarbon) is another important criterion in the planning of CCS deployment. Existing pipelines could be converted to transport CO_2 or be used as a guide to the construction of new ones. The long-term history of underground exploitation as oil and gas activity or geothermal energy in the region would help to engage local population in a CO_2 storage project.

[6] https://totalenergies.com/fr/expertise-energies/projets/bioenergies/grandpuits-biocarburants-bioplastiques
[7] http://www.consultations-publiques.developpement-durable.gouv.fr/IMG/pdf/perecherches.pdf

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

Despite the estimate of storage capacity of the Dogger fm. is still immature and theoretical, Dogger saline reservoirs in the vicinity of Melun (20 km from the emitter) have showed good reservoir properties in the geothermal production-wells. Citizens living in the area are used to the oil and gas activity and many of them are directly employed by these activities. An industrial facility is already capturing more than 400 kt of CO_2 per year and would provide high quality of CO_2 for the storage pilot plant. This facility employs 400 jobs directly and indirectly. CCS technology could offer an attractive option to reach CO_2-reduction targets in the department and in the administrative region of "Ile de France" by 2030.

Concerning the Paris Basin site characterization in PilotSTRATEGY, a 3D seismic acquisition using an innovative non-intrusive approach, i.e: no explosive, no cables, no drilling, is planned for April-May 2022. Data will become public. A dedicated report will detailed the seismic design and the field acquisition work. The 3D seismic acquisition comprises an area of around 10 km^2, which will be the target of forthcoming studies of the project including social sciences, geoscience studies, engineering work, and risk management framework.

3. Inventory of available data – Dogger Fm.

Hydrocarbon production and geothermal energy studied and exploited the Dogger Fm since 1950s. Many data and information is available for the Dogger Fm at basin scale. A description of the available data in the area around the emitter, as well as on a Regional scale (hundred of kms around the emitter) is presented in this section. National and International projects supplying data and information are listed by category of the data discipline. This list is not exhaustive, as more projects and information could become available in the course of the PilotSTRATEGY project.

3.1 Geoscience data

Many projects have studied the Dogger Fm. at basin scale and regional scale. The following projects supply geoscience information of the Grandpuits area. Data from projects cited below are public or are part of the background information of the project partners.

3.1.1 Geology, petrohysics and 3D modelling

GESTCO[8] (European project FP5-EESD)- European potential for geological storage of co2 from fossil fuel combustion (2003) – Screening of potential reservoir in Paris Basin for geological storage of CO_2. GESTCO made a first evaluation of storage capacities of CO_2 in low enthalpy geothermal reservoir in the Paris Basin. Evaluation of technical solutions for CO_2 storage in geothermal reservoirs and the evaluation of the costs.

ANR-SHPCO2[9] (French National Agency) - Simulation Haute Performance du stockage géologique de CO_2 (2012). The 3D geological and petrophysical model of the Dogger at the basin and regional scale are available. These models were used to carry out CO_2 injection simulation to study the hydrodynamic behavior of the reservoir (TOUGH software) and the reactive-transport (Coores-Arxim code).

[8] https://cordis.europa.eu/project/id/ENK6-CT-1999-00010/fr
[9] https://anr.fr/Colloques/Energies2012/presentations/SHPCO2.pdf

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

Geothermal Atlas (BRGM) - Caritg et al. (2018) – Mapping of geothermal targets in France of temperature > to 90° C. Detailed maps at Regional level are available.

ANR-UpGeo (French National Agency) - UPscaling and heat simulations for improving the efficiency of deep GEOthermal energy (2023). Upscaling of measured permeability in samples to reservoir scale sedimentary connectivity. This project is building an exhaustive database of petrophysics measures in core plugs to correlate with wellbore logs and to build a 3D geological and petrphysical model of the Dogger. The area covered by UpGeo project extends to from the Nord of Paris town to Melun (town). Melun is located at 30 km to the West from Grandpuits facilities.

RTPG-PICOREF (Réseau des technologies pétrolières et gazières) is a project that investigated the storage of CO2 in the Paris Basin (2005-2006). This project looked at the possibilities of storage of CO2 in France including aspects regarding safety with works such as the investigation of regulatory framework and environmental aspects (Blanchard, 2006), work on the seismic risk (Roullé, 2006) that lead to identifying an area of the Paris Basin that is characterize by a no seismicity area (Figure 7). Work as also been done on:

- Geophysical investigation (other than seismic) to follow the geological storage (Fabriol and Debeglia, 2006).
- Reactive transport (Lanini and Kervévan, 2007) and coupling chemistry and transport (Kervévan et al, 2007).
- 3D modeling of CO2 injection in the Dogger (Durst and Kervévan, 2007)
- Fracture investigation (Dezayes, 2007)

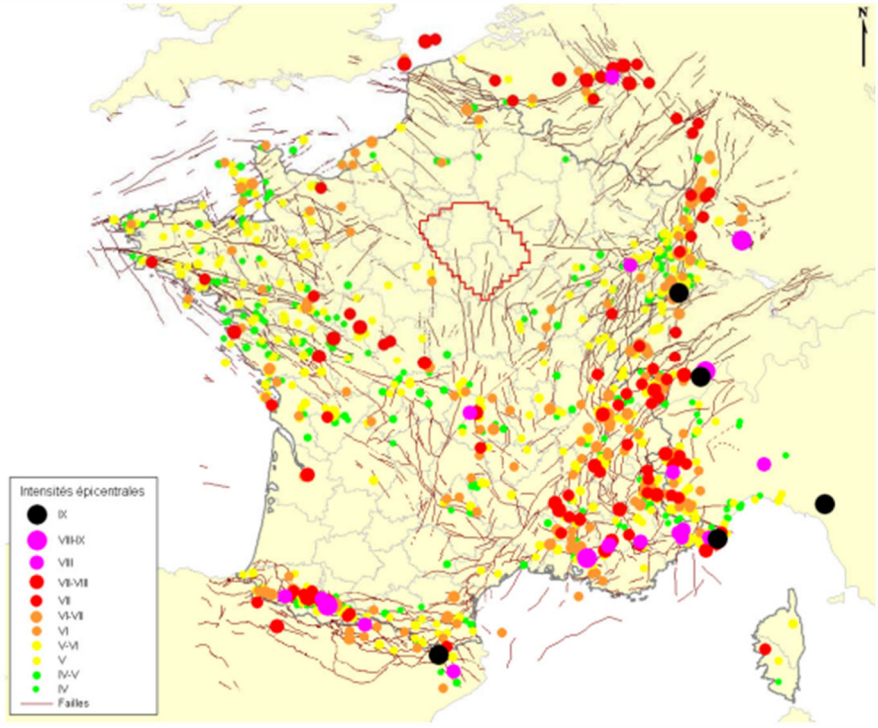

Figure 7: Seismicity in France, the red polygon shows the area selected for the work in PICOREF RTPG (Roullé, 2006)

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

ANR-PICOREF[10] (French National Agency) - Pilote d'Injection du CO_2 dans des Reservoirs géologiques en France (2006-2008). The project was the direct follow-up of the PICOREF financed by RTPG cited previously and also focused on the characterization of CO_2 storage in the Paris Basin. The area of interest has been focused compared to RTPG-PICOREF but the specific target remains the Triassic clastic reservoirs and the Dogger carbonate reservoirs. The overview of the project can be seen in the OGST publication of Brosse et al. (2010). The selected area more focused area south-east of Paris within the no seismic area identified in PICOREF (RTPG). Correlation of wells have been made and the PICOREF sector (Figure 8) has been modeled considering a wider area referred as the "regional domain".

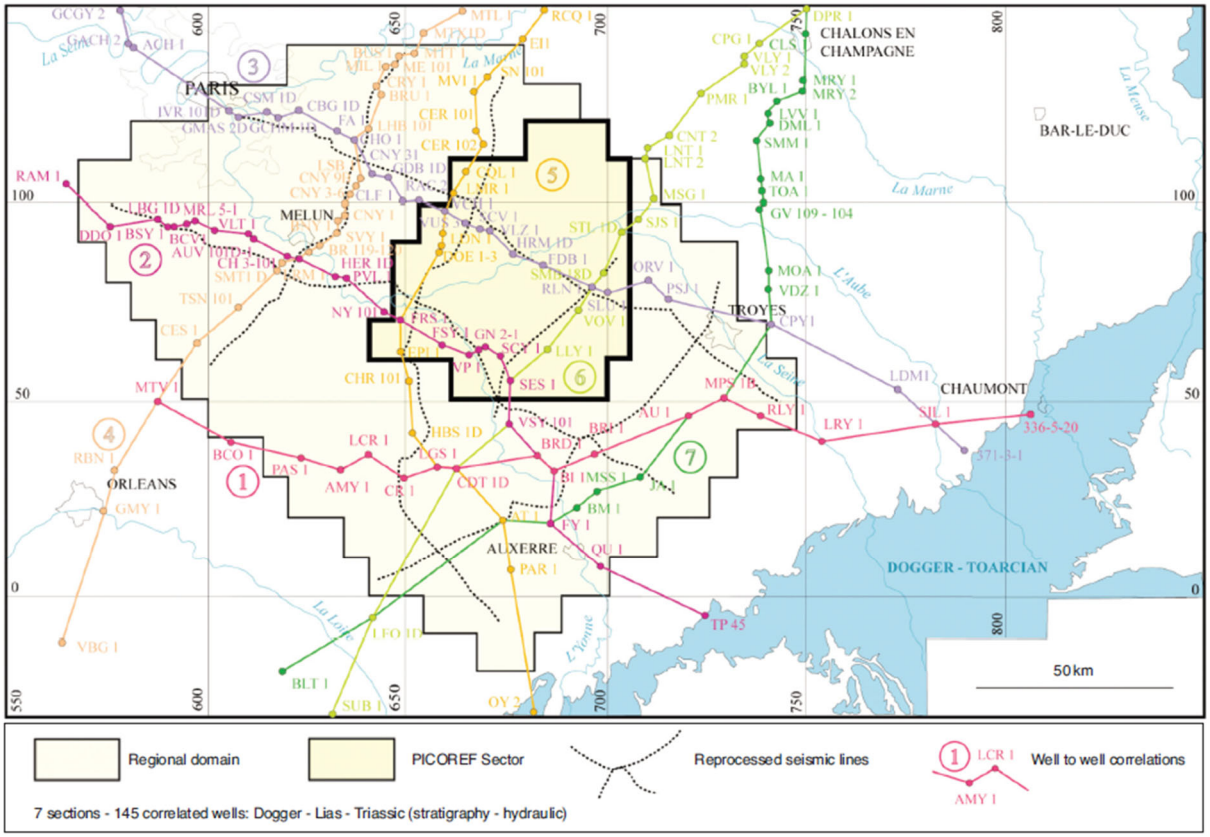

Figure 8: Extension and wells considered in the PICOREF project (Brosse et al, 2010)

The data available in PICOREF cover a wide range of information that have been gathered into geological model coordinated by the BRGM (Grataloup et al, 2008). This modelling encapsulates an area (see extension in Figure 9) with an extension to the west beyond the core "PICOREF area" described in Figure 8. This modelled area includes the Nangis area (see Figure 9) that is of interest in our project.

[10] https://anr.fr/Projet-ANR-05-PCO2-0005

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

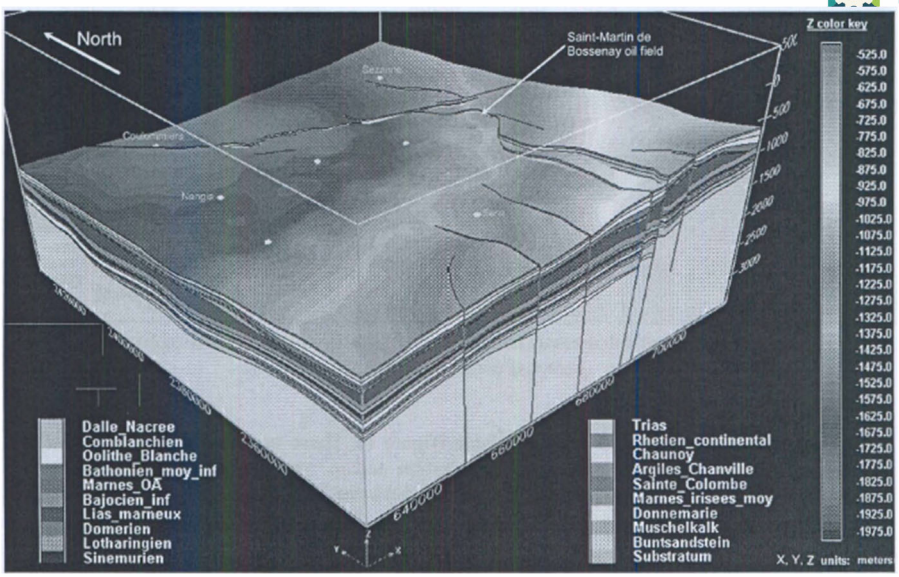

Figure 9: Model from Trias base to top dogger around the PICOREF area (Grataloup et al. 2008).

As part of the ANR-PICOREF project an important effort has been made on the petrophysical analysis (Delmas, 2007). On the cores measurements of permeability, porosity, and matrix density have been done with 6000 values in 70 wells within the PICOREF sector and 1000 values in 16 wells at close proximity to the PICOREF sector. Additional data of calcimetry, age, formation, and texture have also been collected. In addition, 75 wells have had a porosity-permeability-density log. The results obtained by this work gives the following average values show in Table 1.

Table 1: Average porosity and permeability of the Dogger carbonate aquifer (Delmas, 2007)

	Porosity	Permeability
Lower Callovian (Dalle nacrée)	5.5 %	1 D
Upper Bathonian (Comblanchien)	4 %	3.8 D
Upper Bathonian (Oolithe Blanche)	14.5 %	> 10 mD

3.1.2 Geomechanics

Pressure increase in the reservoir due to CO_2 injection will induce a deformation which may trigger integrity issues of the cap-rock, faults instability, and significant surface displacements. In order to address these risks, numerical simulations based on a 3D coupled hydro-mechanical model will be performed. Evaluation of in-situ stresses as well as mechanical properties of reservoir and caprock formations is needed. A previous CO_2 injection modelling study into Dogger carbonates at Saint-Martin-de-Bossenay sector was carried out as part of the GeoCarbone project [Brosse et al. 2010]. In this project, a coupled flow-geomechanical model has been proposed [Vidal-Gilbert 2009].

World stress map data indicate maximum horizontal principal stress oriented around N150° in Paris basin.

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

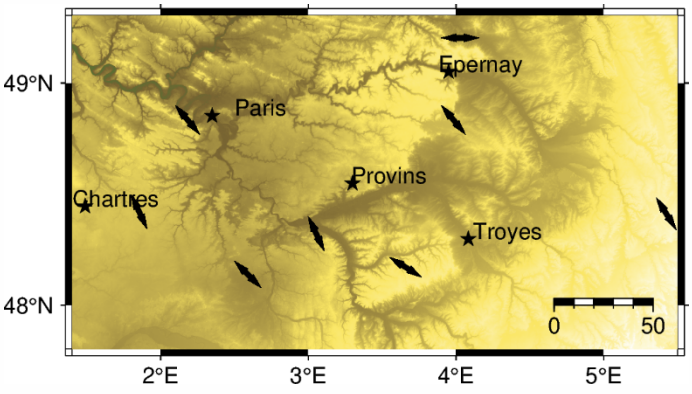

Figure 10: orientation of maximal horizontal principal stress in Paris basin from WSM data.

Willeveau et al (2007): σh≈8 MPa (constant) in Dogger and above argillite, in the limestone formation. Major principal stress is horizontal oriented N150°±10°. 1.4<=σH/σh<=2, high value.

Gunzburger & Cornet (2007) studied the stress field at Bure in the eastern Paris basin. They give values of mechanical properties in Dogger formation.

Table 1. Average physical and mechanical properties of the different lithological units derived from classical laboratory tests (*) and from borehole sonic logging (**). Static and dynamic parameters are in good agreement in the case of the limestone formations, whereas the average static Young's modulus of the argillite is four to five times lower than the dynamic one. Such a contrast may be attributed to non-elastic deformation during laboratory tests, possibly associated with short-term creep.

		Bulk ($g\ cm^{-3}$) density	Static Young's modulus (GPa)*	Static Poisson's ratio*	UCS (MPa)*	UTS (MPa)*	Dynamic Young's modulus (GPa)**	Dynamic Poisson's ratio**
Oxfordian limestone		2,50 ± 0,12	15–40	?	25–75	?	38 ± 10	0.3 ± 0.02
Bure argillite	A unit	2,44 ± 0,08	5,4 ± 1,5	0,3 ± 0,05	29 ± 12	2,7 ± 1,5	21 ± 4	0.2 ± 0.1
	B - C units		4,0 ± 1,5		21 ± 7			
Dogger limestone		2,63 ± 0,05	38 ± 15	0,23 ± 0,05	53–120	2,4–8,3	46 ± 3	0.3 ± 0.01

Masson et al (2019): there is a NE-SW shortening in Paris basin (0.8 10^{-9}/year) part of a large scale shortening in central and western France. There is a small subsidence of -0.3mm/year in Paris basin.

3.1.2.1 In-situ stress

[Gunzburger 2014] summarize several places in Paris Basin where stress data are available (orientations and maximum principal stresses ratios). Two major stresses measurement campaigns have been conducted in Bure sector by Andra for nuclear waste storage proposal. In-situ stresses for Dogger carbonates, Callovo-Oxfordian claystones and Oxfordian carbonates formation have been characterized. Obtained results presented in [Willeveau 2007], [Cornet 2010] and [Cornet 2012] show a maximum horizontal stress (SH) orientation of N150E ± 15°. The maximum horizontal to vertical stress ratio (SH/Sv) tend to 1 with depth, while the minimum horizontal to vertical stress ratio (Sh/Sv) range between 0.8 and 0.6 with a lower deviatoric stress observed in clay-rich formations.

In [Vidal-Gilbert 2009] a maximum horizontal stress (SH) azimuth of N150°E has been deduced from breakouts analysis of SMB17 and SMB18, an average minimum horizontal to vertical stress ratio Sh/Sv = 0.7 has been defined from hydraulic fracturing tests, and the SH/Sv ratio has been fixed to 1 based on literature data.

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

These measurements are in agreement with data from [Cornet 1992] in the Massif Central, and more generally, with regional orientation and magnitude observed at the basement level [Heidbach 2018], [Muller 1992].

3.1.2.2 Material properties

[Vidal-Gilbert 2005] described a methodology to estimate elastic properties from velocities and density log relying on Biot-Gassman equation and Wang correlation. Moreover, correlation between p-velocities and porosities in limestone when depositional environments and diagenetic processes are known have been established by [Brigaud 2010]. Such approach can be used to estimate elastic properties based on logs found in the vicinity of Grandpuits area.

An alternative approach is to consider analytical models. [Bemer 2004] proposed a methodology to infer elastic and plastic properties from porosity for limestones, and from porosity/mineralogy for sandstones. Models are simple and obtained results are in agreements with experimental and literature data.

Concerning the characterization of the Callovo-Oxfordian claystone behaviour, several works have been published. In [Armand 2017], Young modulus measurements together with mineral content are available at shallow depth (500 to 600m), obtained average values are between 6 and 12 GPa influenced by the calcite content. A homogenization model validated on these data has been proposed by [Guery 2008] and may be used to extrapolate properties at lower porosities.

Additional uniaxial and triaxial tests results are published in [Chiarelly 2003], [Belmokhtar 2017]. [Menaceur 2015] has referenced experimental works focused on the characterization of plastic properties of the claystone. Average values deduced from these works are close to 21° for the friction angle without strong deviation at considered porosities, while cohesion range is between 3.9MPa at 12% porosity and 1.94MPa at 17%.

In [Vidal-Gilbert 2009], elastic properties are deduced from velocity and density logs from the well SMB17. Identified properties are approximately 24GPa for the reservoir (at 15% porosity) and 13.5GPa in the caprock (at 5% porosity). Friction angles and cohesions were obtained from empirical correlation for the reservoir [Bemer 2004] and extrapolated from published triaxial test on Callovo-Oxfordian samples for the caprock. Retained values for reservoir are 9.5MPa for cohesion, 40.8° for friction and for caprock, 9MPa and 20°.

3.1.3 Geochemical characteristics

The Dogger formation is the main geothermal aquifer exploited in the Paris region. Geothermal operations, developed since the early 1970s, allowed access and sampling of the reservoir fluids at a regional scale. Accordingly, a large number of water samples and physico-chemical analyses are available at the periphery of the PilotSTRATEGY new prospective area. Rojas et al. (1989) compiled and discussed the most comprehensive chemical analyses of the geothermal fluids, including both water and gas composition.

From a general approach, the water of the Dogger aquifer is classified as a sodium-chloride type water, with a salinity between 5.8 and 35 g/l and temperatures between 47 and 85°C, in the center of the Paris basin. Groundwater temperature and salinity decreases towards the outcrops – e.g. in the South of the Paris Basin (Fontainebleau, Evry, Corbeil; Figure 11) – due to dilution by meteoric waters (Rojas et al., 1989). The areas with the most saline and warmest groundwater are located in the topographic troughs (Meaux, Coulommiers ; Figure 1), which contain brine waters (> 30 g/l). A hypothetical upflow

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

of brine groundwater originating from the Triassic aquifer – through vertical faults – has been proposed to explain the occurrence of brine groundwater and/or the slight SO_4 enrichment identified locally in the Dogger aquifer (Maget, 1991; Michard et Bastide, 1988; Wei, 1986). The PilotSTRATEGY new prospective area being located between Melun and Coulommiers, a groundwater of intermediate salinity and temperature is expected in the Dogger aquifer – i.e. based on the existing scientific literature.

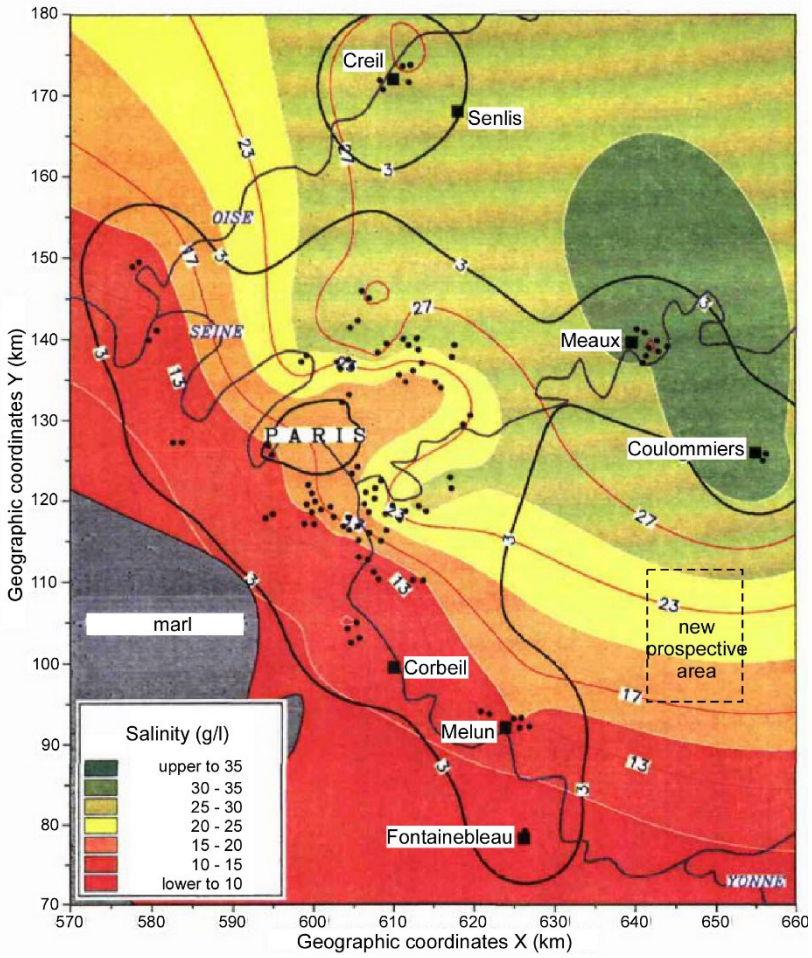

Figure 11: Map of the groundwater salinity in the Dogger aquifer of the Paris Basin (Rojas et al., 1989)

On a local scale, variations in hydrogeochemistry between the top and the bottom of the Dogger aquifer occurs, but the variations remain low with respect to major elements. Such general pattern led to neglect vertical drainages and exchanges between the stratified Dogger layers and thus consider a homogenous salinity and chemical composition with respect to depth within reactive transport models to simulate supercritical CO_2 injection (André et al., 2007; Mathurin et al., 2017) or geothermal operation (Castillo et al., 2011; Marty et al., 2020) of the Dogger aquifer.

In term of mineralogy, the composition of the Dogger formation was characterized from cores from Aulnay-sous-Bois and Cergy for primary minerals in the 1990's, whereas accessory minerals were defined by calculation of the thermodynamic equilibrium of the Dogger pore water (Saturation Indexes) with respect to mineral phases (Azaroual et al., 1997; Coudrain-Ribstein et Gouze, 1993;

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

Michard et Bastide, 1988). André et al. (2007) proposed an assemblage mainly composed of carbonates and aluminosilicates minerals. The mineralogical assemblage consists essentially of calcite and dolomite, whereas siderite, illite, albite and K-feldspars are considered as accessory minerals. Such mineral assemblage has ever since been used as a reference within the geochemical and reactive transport modelling simulations applied in the Dogger aquifer (André et al., 2007; Castillo et al., 2011; Gille, 2010; Marty et al., 2020; Mathurin et al., 2017).

In the RTPG-PICOREF, reactive transport (Lanini and Kervévan, 2007) and coupling chemistry and transport (Kervévan et al, 2007) have been investigated.

As part of the ANR-GéoCarbone-PICOREF project, the investigation of the temperature and salinity has been done in both Triassic and Dogger reservoirs. The results of this work by Monnet (2006) is synthetized in a confidential report with numerous data. In the ANR-PICOREF area the Dogger has a temperature estimated between 46 and 69°C and a salinity between 1 and 20 g/l and in the Triassic a temperature between 80 and 115 °C for a salinity between 1.8 and 200 g/l.

3.1.4 Seismicity

The seismicity in the Paris Basin has been investigated by Roullé (2006) in the framework of the PICOREF-RTPG (see the section 3.1.1). The conclusion of this work is that within the area investigated (Figure 12) is not showing any seismic activity (measured) but the area at the north with the proximity with the Bray Fault as a potential source of seismogenic activity.

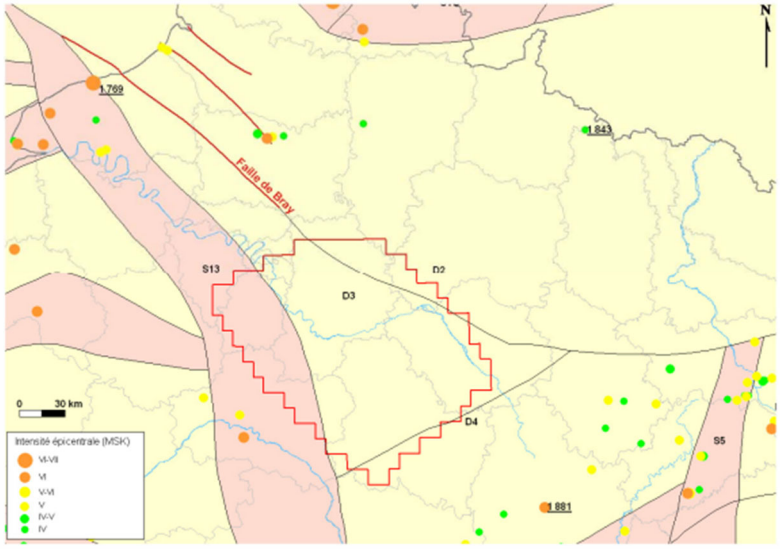

Figure 12: Seismotectonic zonation with the selected area for PICOREF-RTPG in the red polygon (Roullé, 2006)

3.1.5 Injection and injectivity

CLASTIQ-2 (ADEME, French Ministry) - Ressources géothermales des réservoirs clastiques en France (2012).

ANR GeoCarbone-Injectivité (French National Agency)[11] – Study of optimal conditions to inject CO_2 in the carbonate reservoir of the Dogger (2008). Analytical calculations and scenaria of CO_2 injection taking into account thermo-physics and thermo-dynamic behavior of CO_2 in the reservoir, wellbore modelling and geochemical modelling.

[11] https://anr.fr/Colloques/NTE2009/pdf/5/CO22005%20INJECTIVITE%20resume_bilan.pdf

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

3.1.6 Hydrogeology

The Dogger formation is a deep aquifer in the center of the Paris basin, with the top of the aquifer situated between -1073 mNGF (Beauvais) and -1847 mNGF (Coulommiers) and pressure ranging from 134 bars (Beauvais) to 211 bars (Coulommiers) (Rojas et al., 1989). The Dogger aquifer naturally flow overall towards the north-west of the Paris basin (Figure 13), with a regional flow velocity estimated to about 1 m/year (Wei, 1986), although flow velocities appear to be higher in the southern part of the Paris Basin (Aubertin et Ballin, 1984). However, from the current knowledge (Figure 13), the water table of the aquifer displays a natural hollow shape in the PilotSTRATEGY new prospective (hydraulic head ≤ 140 mNGF), meaning that groundwater may naturally flow from Fontainebleau (hydraulic head > 180 mNGF) and Coulommiers (hydraulic head > 160 mNGF) toward the prospected area.

The cumulative thickness of the productive levels of the Dogger formation is in the range of 5.5 m (L'Hay les roses) and 47 m (Mée-sur-Seine). The thickness of the hydraulically conductive layers of the aquifer overall decreases towards the East of the Paris Basin (Rojas et al., 1989). An estimated thickness of 20 m is expected in the PilotSTRATEGY new prospective area. The porosity of the hydraulically conductive layers of the formation varies from 10 (Chevilly-la-rue) to 23.5% (Aulnay-sous-Bois) (Gille, 2010; Rojas et al., 1989), with a theoretical porosity estimated between 14 and 18 % (Meaux and Coulommier) in the new area of study. The hydraulically conductive layers of the formation display a large range of intrinsic permeability, varying from 2.30 x 10^{-6} m/s (Fontainebleau) and 6.90 x 10^{-5} m/s (Bondy) (Gille, 2010; Rojas et al., 1989).

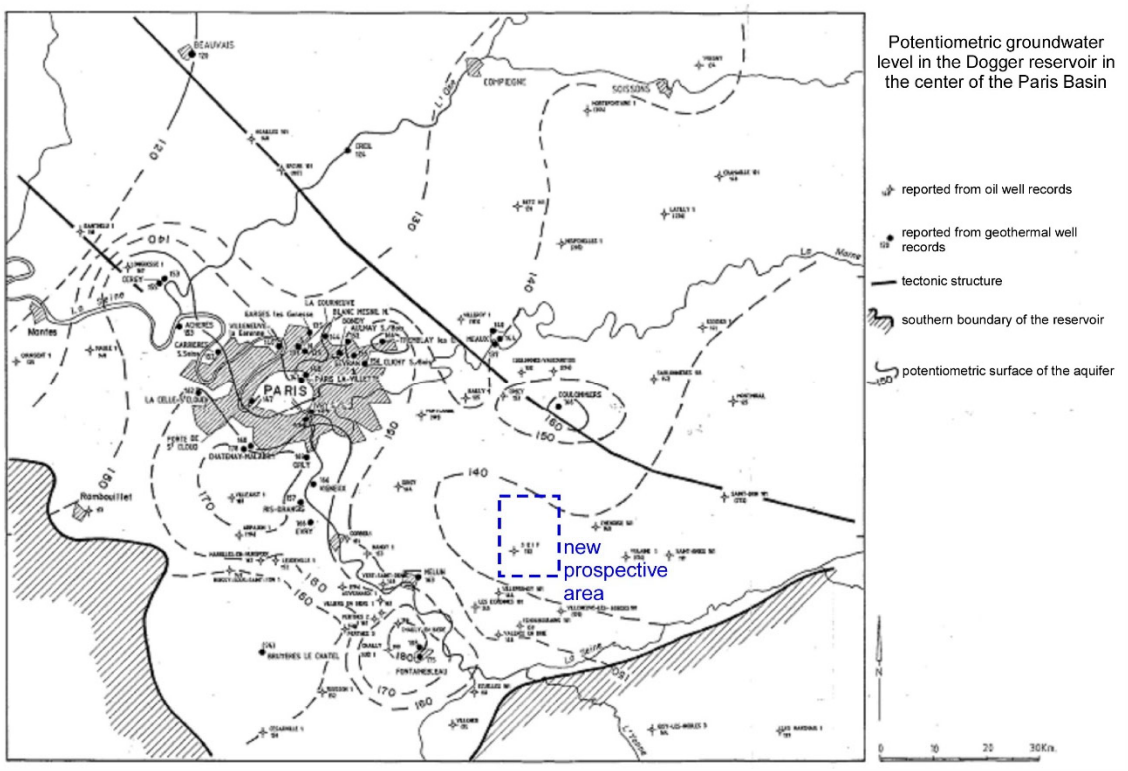

Figure 13: piezometric map of the Dogger aquifer in the center of the Paris Basin (adapted from Aubertin et Ballin, 1984).

Information regarding the Hydrogeology in the Triassic reservoir is available from the PICOREF project (see confidentiality regarding the project in section 143.1.1). The information relates to the Master project of A. Dufournet (2007) that had the focus to create a 3D hydrogeological model of the PICOREF sector. The model uses data that have a larger extension (inc. geological structure,

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

lithological facies, porosity, permeability, salinity, …) to obtain the natural hydrothermal flow and a simulation of CO2 injection.

3.1.7 Geography

Grandpuits is located in the Paris area, some 60 km to the South-East of Paris. The nearby city of Provins is situated 25km to the East and counts some 12,000 inhabitants. To the West at about the same distance is the city of Melun (not shown on this map) which counts some 40,000 inhabitants. Grandpuits thus sits in the Ile de France region, number one of the 13 regions of continental (metropolitan) France; with about 20% of the French population, it is the most populated region in France, and generates nearly 30% of the French Gross Domestic Product (GDP).

The site of Grandpuits is part of the commune of Grandpuits-Bailly-Carrois, itself part of the Community of communes of Brie Nangissienne, a grouping of 20 communes counting a total of about 28,000 inhabitants (figure D below). The largest commune, Nangis, with about 8,800 inhabitants, is the capital city for this Community of communes.

The Seine and Marne is also a large water reservoir for Paris with the Champigny aquifer and source water (e.g. Voulzie), hence the precautions that are taken not only by industry but today by agriculture as well to eliminate or reduce pollution from fertilizers and pesticides in the water. This "sustainable agriculture" involves all the departmental players such as Chamber of Agriculture, House of livestock, General Council, Basin Agency, Departmental directorate of territories (DDT), etc

4. Gap analysis

Despite a lot of data being available in the area or nearby to the selected area, some information should be acquired for the technical characterization of the storage complex. New data is planned to be acquired in the WP2 (Geo-characterization) for the characterization of reservoir and seal rocks and their interaction with CO_2-rich fluids. These data are:

- Petrophysics: rock properties from both physical samples (core and cuttings) and digital measurements (well logs). Reservoir samples: Porosity and clay bound water; Pore size distribution by mercury injection; Permeability and formation factor; Irreducible water saturation. Caprock samples: gas entry pressure
- Geochemical: optical microscopy and X-Ray Diffraction (XRD) identification of potentially reactive mineral phases; and mineral surface microtextures characterised by Scanning Electron Microscopy to identify changes after exposure to CO_2. Batch reaction and flow through vessels will provide reaction rates for the reservoir minerals on exposure to CO_2. Relative permeability curves for the CO2-brine system under drainage and imbibition for the selected reservoir rocks.
- Geomechanical: For geomechanical properties, the tensile strength will be determined from Brazilian tests. From uniaxial tests, the uniaxial compressive strength and the static elastic moduli will be determined. And finally dynamic elastic moduli will be determined from ultrasonic velocity measurements.

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

Other data and information listed in this section is related to the Paris Basin area and its specificities. The reservoir and caprock system are well-known in the area. The upper part of the Dogger Fm, the Callovian, is an oil field being exploited in other areas of Paris Basin. Most of data available from cores samples concerns this upper part of the Dogger reservoir. As the target reservoir here is the lower part of the Dogger Fm, the Bathonian, cores and data available from core samples are scarce.

Formation water composition and samples are available in the nearby oil-fields. French partners have requested the oil-field operator to access this data for the geochemical analysis and modelling foreseen in the WP2.

The new 3D seismic will allow characterization of faulting at the scale of the seismic with a resolution of approximatively 30 meters. Smaller faults and fractures should be characterized by integration and interpolation of observations at seismic scale (tens of meters) and core scale (centimeter to meter). Outcrop studies could be useful to populated facies models, which have a resolution between seismic and core scales.

The selected area for the full characterization was studied in the past during the hydrocarbon exploration works. Therefore, five “dry” wells were drilled the entirely Dogger Fm in the prospective area (Figure 14). These wellbores should be investigated in detail regarding mainly their cementation and current casing quality, as these are the most likely leakage pathways. Further, the possibility to use these wellbores as monitor wells should be assessed.

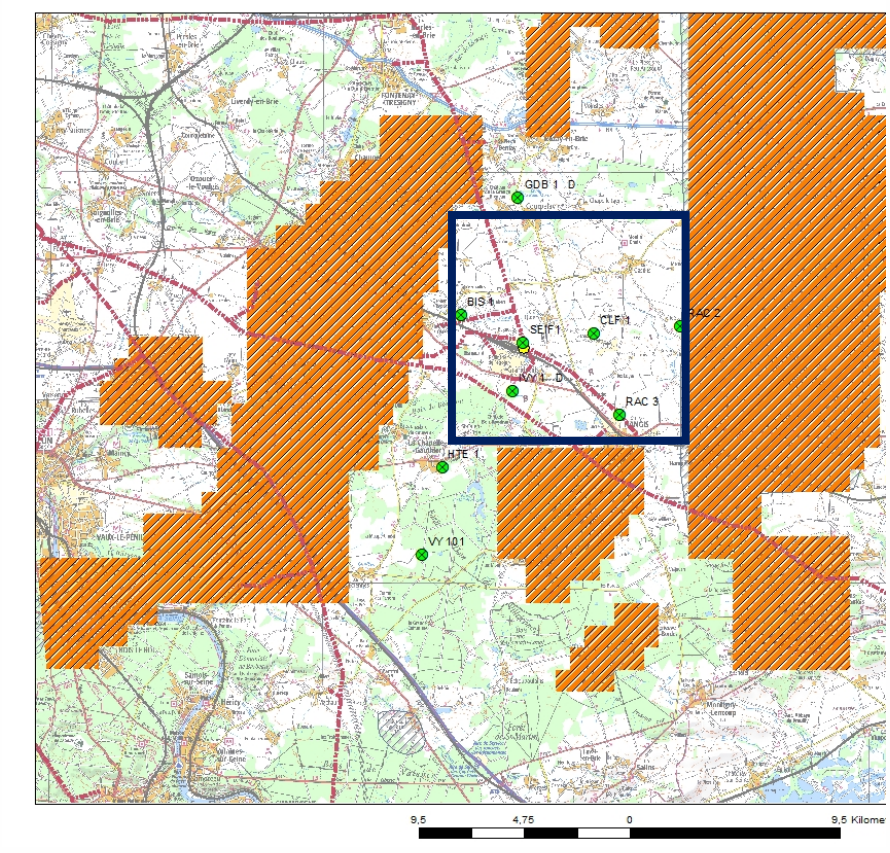

Figure 14: Dry wellbores (green points) in the selected area for the seismic acquisition is delimited by the square.

The PilotSTRATEGY project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 101022664

5. References

André, L., Audigane, P., Azaroual, M. and Menjoz, A. (2007) Numerical modeling of fluid–rock chemical interactions at the supercritical CO2–liquid interface during CO2 injection into a carbonate reservoir, the Dogger aquifer (Paris Basin, France). Energy Conversion and Management 48, 1782-1797.

Armand G., Conil N., Talandier J, Seyedi D. (2017), Fundamental aspects of the hydromechanical behaviour of Callovo-Oxfordian claystone: From experimental studies to model calibration and validation, Computers and Geotechnics, Volume 85, Pages 277-286.

Aubertin, G. and Ballin, F. (1984) Analyse des écoulements naturels dans l'aquifère géothermique du Dogger du centre du bassin de Paris, BRGM/ 84 SGN 79 GTH-IRG. Institut mixte de recherches géothermiques.

Azaroual, M., Fouillac, C. and Matray, J.M. (1997) Solubility of silica polymorphs in electrolyte solutions, II. Activity of aqueous silica and solid silica polymorphs in deep solutions from the sedimentary Paris Basin. Chemical Geology 140, 167-179.

Batel, S., Devine-Wright, P., Wold, L., Egeland, H., Jacobsen, G., Aas, O., 2015. The role of (de-) essentialisation within siting conflicts: an interdisciplinary approach. J. Environ. Psychol. 44, 149–159. https://doi.org/10.1016/j.jenvp.2015.10.004

Belmokhtar, M., Delage, P., Ghabezloo, S. et al. (2017) Poroelasticity of the Callovo–Oxfordian Claystone. Rock Mech Rock Eng 50, 871–889.

Bemer, E., Vincké, O., and Longuemare, P. (2004): Geomechanical Log Deduced from Porosity and Mineralogical ContentOil & Gas Science and Technology - Rev. IFP, 59 4, 405-426

Blanchard, F., (2006). Piégeage du CO2 dans les réservoirs géologiques en France : projet PICOREF, cadrage réglementaire et enjeux environnementaux. Rapport BRGM RP-54638-FR.

D. Bonijoly, A. Fabbri, F. Chapuis, Audrey Laude, O. Ricci, et al.. Technical and economic feasibility of the capture and geological storage of CO2 from a bio-fuel distillery: CPER Artenay project. Energy Procedia, Elsevier, 2009, 1 (1), pp.3927-3934. ⟨10.1016/j.egypro.2009.02.196⟩. ⟨hal-02163814⟩

Bonijoly D., with the collaboration of Barbier J., Matray J.M., Robelin C., Kervevan C.,Thierry D., Menjoz A., Cotiche C., Herbrich B. (2003) – Feasibility of CO2 storage in geothermal reservoirs. Example of Paris Basin, France. BRGM-CFG-ANTEA contribution to the GESTCO project. Fifth RTD Framework Programme (ENK6-CT-1999-00010). BRGM/RP-52349-FR, 135 p.

Brigaud B., Vincent B., Durlet C., Deconinck J.F., Blanc P., Trouiller A. (2010): Acoustic Properties of Ancient Shallow-Marine Carbonates: Effects of Depositional Environments and Diagenetic Processes (Middle Jurassic, Paris Basin, France). Journal of Sedimentary Research ; 80 (9): 791–807

Brosse, É.; Badinier, G.; Blanchard, F.; Caspard, E.; Collin, P. Y.; Delmas, J. et al. (2010): Selection and Characterization of Geological Sites able to Host a Pilot-Scale CO 2 Storage in the Paris Basin (GéoCarbone -PICOREF). In Oil Gas Sci. Technol. – Rev. IFP 65 (3), pp. 375–403. DOI: 10.2516/ogst/2009085.

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

Caritg S., Tourlière B. et Bourgine B. (2018) : Cartographie des cibles géothermales de moyenne température pour la production d'électricité et de chaleur parcogénération enFrance métropolitaine. Projet Atlas-CoGTH. Rapport final. BRGM/RP-67853-FR, 2 5 3 p., 11 fig., 8.

Castillo, C., Azaroual, M., Hamm, V. and Jacquemet, N. (2011) Physico-chimie et réactivité des fluides du Dogger du bassin parisien soumis aux conditions de stockage de chaleur, BRGM/RP-60189-FR.

Chiarelli AS, Shao JF, Hoteit N (2003) Modeling of elastoplastic damage behavior of a claystone. Int J Plast (19), 23–45

Cornet, F.H., (2010): Determining the Complete Stress Tensor from Hydraulic Tests: A Case History in Sedimentary Rocks from the French Paris Basin. In: Xie, Furen (Ed.), Rock Stress and Earthquakes, proc. 5th Int. Symp. on in situ Rock Stress, Beijing, China. CRC Press, Taylor and Francis, pp. 77–84.

Cornet, F.H., Röckel, T., (2012): Vertical stress profiles and the significance of "stress decoupling". Tectonophysics 581, 193–205.

Cornet, F.H., Burlet, D., (1992): Stress field determination in France by hydraulic tests in boreholes. J. Geophys. Res. 97 (B8), 11829–11849.

Coudrain-Ribstein, A. and Gouze, P. (1993) Quantitative study of geochemical processes in the Dogger aquifer, Paris Basin, France. Applied Geochemistry 8, 495-506.

Coussy, P. 2021. Deliverable D5.2: Description of CCUS business cases in eight southern European regions, 133p. EU H2020 STRATEGY CCUS. Project 837754.

Delmas, J. (2007). Etude pétrophysique des aquifères du Dogger carbonate dans le secteur Picoref (Sud Champagne, Bassin de Paris) - Relation entre la porosité et la perméabilité mesurée sur carottes. Report IFP 59791.

Devine-Wright, P., Wiersma, B., 2020. Understanding community acceptance of a potential offshore wind energy project in different locations: an island-based analysis of 'place-technology fit.'. Energy Policy 137, 111086. https://doi.org/10.1016/j. enpol.2019.111086.

Dezayes Ch. (2007). Réseau de fractures dans le Dogger de Bourgogne. Données pour le calcul de perméabilité équivalente. Rapport final. BRGM/RP-54955-FR. 77 pp.

Dufournet, A., 2007 (Confidentiel). Un modèle géologique pour simuler le stockage du CO2 dans les aquifères salins triasiques du Bassin de Paris (Secteur PICOREF). Rapport de stage M2, Université Pierre et Marie Curie. Rapport IFP 60167 Janvier 2008, 70 pp.

Durst, P. et Kervévan, C. (2007). Modélisation 3D couplée chimie-transport de l'injection de CO2 à l'échelle d'un site pilote en aquifère salin profond (Dogger, bassin de Paris). Rapport BRGM/RP-55667-FR, 31 pp.

Dütschke, E., Wesche, J., Oltra, C., Prades, A., Álvarez, F. C., Carneiro, J. F., ... & Vulin, D. (2019). Stakeholder mapping report WP3-Deliverable 3.1. EU H2020 STRATEGY CCUS Project 837754.

Fabriol H., Debeglia N. (2006). Application des méthodes géophysiques (autres que sismique) au suivi des stockages géologiques de CO2. BRGM/RP -54975-FR, 38 pp.

France Nord project – Rapport Final Confidentiel (2013). Leaflet: https://www.ademe.fr/france-nord (acessed on December 2020).

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

Gille, A.L. (2010) Suivi Et Modélisation Du Comportement Hydro-géochimique Du Dogger, Soumis à La Réinjection De Fluides « Chaud » Et « Froid », Université Pierre et Marie Curie, École nationale supérieure des Mines de Paris, Centre d'informatique Géologique de Fontainebleau.

Grataloup, S., Thinon, I., Houel, P., Delmas, J., Dufoumet, A., Renoux, P., 2008. A 3D geological model for site selection and characterization in the Paris basin. Conference Proceedings, First EAGE CO2 Geological Storage Workshop, 29 & 30 Sep 2008.

Gravaud, Isaline and M. L. Veloso, Fernanda and Prézélus, Flavie and Bidel, Alexandre and Diallo, Tidjan and Zrida, Mohamed and Malanda, Noémie and Chauzeix, Benoit and Laurent, Faustine and Villeneuve, Jacques and Doucet, Muriel and Lambert, Marie-Odile and Lalizel, Benoit and Combe, Michel, Biomass-Origin Carbon Capture, Storage and Utilization in Greenhouses: The CO2SERRE Project in Centre-Val De Loire (France) (March 25, 2021). Proceedings of the 15th Greenhouse Gas Control Technologies Conference 15-18 March 2021, Available at SSRN: https://ssrn.com/abstract=3812275 or http://dx.doi.org/10.2139/ssrn.3812275.

Guéry A Abou-Chakra, Cormory F, Su K, Shao J-F, Kondo D. (2008) : A micromechanical model for the elasto-viscoplastic and damage behaviour of a cohesive geomaterial. Phys Chem Earth, Parts A/B/C;33(Supplement 1):416–21

Gunzburger Y, Cornet F. (2007) Rheological characterization of a sedimentary formation from a stress profile inversion. Geophysical Journal International, Oxford University Press (OUP), 168 (1), pp.402-418.

Gunzburger Y., Magnenet V., (2014): Stress inversion and basement-cover stress transmission across weak layers in the Paris basin, France, Tectonophysics, Volume 617, Pages 44-57, ISSN 0040-1951.

Heidbach O, Rajabi M, Cui X, Fuchs K, Müller B, Reinecker J, Reiter K, Tingay M, Wenzel F, Xie F, Ziegler MO, Zoback M-L, Zoback M. (2018): The world stress map database release 2016: crustal stress pattern across scales. Tectonophysics. 2018;744:484–98.

Kervévan, C., Lanini, S., Audigane, P. (2007). Etude comparative des algorithmes de couplage des codes chimie-transport utilisés au BRGM : premiers résultats à partir d'expérimentations numériques simples. BRGM/RP-54904-FR, 66 pP.

Lanini, S. et Kervévan, C. (2007). Essai de quantification de l'erreur induite par l'algorithme de résolution numérique du transport réactif. Rapport BRGM/RP-54421-FR, 54 pp

Masson C., Mazzotti S., Vernant P., Doerflinger E. (2019). Extracting small deformation beyond individual station precision from dense Global Navigation Satellite System (GNSS) networks in France and western Europe, Solid Earth, 10, 1905–1920.

Maget, P. (1991) SMAERC, Forage au Dogger de Saint Florent sur Cher, Programme complémentaire pour la détermination du potentiel., Rapport BRGM, R33148 CEN 4S/91, 19 p.

Marty, N.C.M., Hamm, V., Castillo, C., Thiéry, D. and Kervévan, C. (2020) Modelling water-rock interactions due to long-term cooled-brine reinjection in the Dogger carbonate aquifer (Paris basin) based on in-situ geothermal well data. Geothermics 88, 101899.

Mathurin, F., André, L. and Parmentier, M. (2017) Simulation of the impact of SO2 co-injected with CO2 on the reservoir - rock reactivity Goldschmidt Abstracts 2017, 2624.

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

Menaceur H, Delage P, Tang A-M, Conil N (2015) The thermo-mechanical behaviour of the Callovo–Oxfordian claystone. Int J Rock Mech Min Sci 78:290–303

Michard, G. and Bastide, J.-P. (1988) Etude geochimique de la nappe du dogger du bassin parisien. Journal of Volcanology and Geothermal Research 35, 151-163.

Monnet, M. (2006). Inventaire des températures et des salinités des aquifères du Dogger calcaire et du Trias gréseux dans le secteur d'étude de PICOREF (Bassin de Paris : Champagne méridionale). Rapport IFP 59466.

Müller, B., Zoback, M.L., Fuchs, K., Mastin, L., Gregersen, S., Pavoni, N., (1992): Regional stress patterns of tectonic stress in Europe. Journal of Geophysical Research 97 (B8), 11783–11804.

Rojas, J., Giot, D., Le Nindre, Y.-M., Criaud, A., Fouillac, C., Brach, M., Menjoz, A., Martin, J.-C. and Lambert, M. (1989) Caractérisation et modélisation du réservoir géothermique du Dogger Bassin Parisien, France, BRGM/IRG SNG 89/R 30 169. BRGM, p. 251.

Roullé A. (2006). PICOREF : Piégeage du CO2 dans les réservoirs géologiques en France. Évaluation du risque sismique. Rapport final BRGM/RP-54675-FR, 27 pp.

Veloso, F. M. L. 2021. Maturity level and confidence of storage capacities estimates in the promising regions. Paris Basin section. EU H2020 STRATEGY CCUS Project 837754, Report, pp 125.

Vidal-Gilbert, S., Huguet, F., Assouline, L., Longuemare, P., (2005): Hydromechanical modelling of reservoir behaviour during underground gas storage exploitation, European Association of Geoscientists and Engineers, Proceeding of the 68th Conference & Exhibition, Madrid, Spain

Vidal-Gilbert, S.; Nauroy, J.-F.; Brosse, É. (2009): 3D geomechanical modelling for CO2 geological storage in the Dogger carbonates of the Paris Basin,. In Int. J. Greenhouse Gas Control 3, pp. 288–299.

Von Rothkirch, J., & Ejderyan, O. (2021). Anticipating the social fit of CCS projects by looking at place factors. International Journal of Greenhouse Gas Control, 110, 103399. https://doi.org/10.1016/j.ijggc.2021.103399

Wileveau, Y., Cornet, F.H., Desroches, J., Blumling, P., (2007): Complete in situ stress determination in an argillite sedimentary formation. Physics and Chemistry of the Earth 32 (8-14), 866-878.

Wolsink, M., 2007. Planning of renewables schemes: deliberative and fair decisionmaking on landscape issues instead of reproachful accusations of non-cooperation. Energy Policy 35, 2692–2704. https://doi.org/10.1016/j.enpol.2006.12.002

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664