Petrophysical characterization of Triassic and basement formations for geothermal purposes in the Paris basin: from sub-surface data to reservoir outcrop analogue

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ABSTRACT

A coupled study on deep cores from the Paris basin brings new insights for the geothermal potential of the area on both sedimentary and basement geological units. Petrophysical and petrographic results of continental successions from Upper Triassic formations show that the western edge of the Paris basin can deliver fairly good reservoir properties (5-23% porosity and 5-800 mD permeability) with a the best quality index found in fluvial facies types along the continental deposition profile. The burial of the sedimentary sequence affects the reservoir quality with appearance of several diagenetic phases (dolomite and calcite cements) and feldspar dissolution to a lesser degree. In parallel, an analytical work is conducted on basement rocks from deep cores and combines petrography and petrophysics for identifying potential structures for hot water circulation in the Variscan basement, displaying mineralogical testimonies of paleofluids. These targets in the Paris basin are part of a broad scale European project called MEET, for Multidisciplinary and multi-context demonstration of EGS exploration and Exploitation Techniques and potentials. This project aims to increase the geothermal market at European scale by means of original exploitation techniques and the identification of untapped geothermal resources of various geological contexts of Europe.

1. INTRODUCTION

The sedimentary successions located at 2-3 kilometres of depth in the intracratonic Paris basin are the target of geothermal prospection as part of the European project MEET, which aims to develop Enhanced Geothermal Systems (EGS) technologies in various geological contexts selected in Europe. Many geothermal operations are using the Middle Jurassic (Dogger) carbonates of the Paris basin as hot water reservoirs, resulting in a progressive drop in the aquifers temperature; this is the result of 30 years production from 40 plants using 112 drilled wells (Hamm et al., 2012). The deep reservoirs of the Paris basin (2000-3000 m) such as the Upper Triassic and the Variscan basement stand for possible alternative geothermal resources, with higher temperatures (80-150 °C) than the Dogger reservoirs.

Siliciclastic formations deposited during the Upper Triassic are widely exploited by oil & gas companies in the Paris basin, which provide valuable data for reservoir characterization. The geothermal potential of these formations is mostly controlled by thermal storage capacities of sandstones and depositional organization upon which depends the intergranular porosity within sand bodies that has a strong influence on the reservoir flow properties. These sedimentary deposits have proven to be good reservoirs when sufficiently thick and spatially extended (Hornung & Aigner, 2002). For the Chaunoy formation that stands for one of the most favourable reservoirs (Bouchot et al., 2012), the transmissivity is guided by the distribution of permeability and porosity in the stacked layers as well as depositional environments. Despite lateral facies variability, such stratigraphic interval is currently extensively explored for heat transfer modelling (Hamm et al., 2016; Hamm & Lopez, 2012). However, studies of siliciclastic reservoir organization have to be carried out both on cores and field analogues, as recommended for upscaling purposes in order to transpose knowledge from borehole to reservoir (Bouchot et al., 2008). This kind of approach is needed for successful exploitation of the Triassic formations and is developed in hereafter.

Metamorphic to crystalline rocks of the Variscan basement can provide additional targets for the exploration of geothermal resources in the Paris Basin. The basement rocks encountered in drillings are diverse and in continuity with those cropping out in the basement massifs (Baptiste, 2016). The access to borehole data in the frame of the MEET project provides a unique opportunity to investigate these rocks and the potential for geothermal fluids to flow through, by studying petrographic textures and petrophysical properties. Some mineralogical characteristics found in cores could indicate fluid circulation through structural discontinuities of Variscan age or younger and alteration zones, either hydrothermal or weathered, as already known at Soultz-sous-Forêts and Rittershoffen (Dezayes & Lerouge, 2019; Kushnir et al., 2018; Ledésert et al., 2010).

The purpose of this paper is three-fold: 1) to provide a crossed methodology coupling sedimentology, petrography and petrophysics on siliciclastic geothermal reservoirs, 2) to bring some exploratory results of Triassic reservoirs from boreholes in Paris basin and field analogue in Ardèche; 3) to present the material and techniques considered for deep-seated undercovered basement rocks collected from the Paris basin.

2. COUPLED SEDIMENTOLOGICAL AND PETROPHYSICAL STUDY OF TRIASSIC RESERVOIRS

In the Paris basin and surrounding areas, the Triassic sediments formed under a hot and humid climate during the early stage of breakup of Pangea supercontinent that followed the Variscan orogeny. The siliciclastic material came from the erosion of subsequent massifs that created flat lands dominated by gravity-driven flowing processes towards the Germanic Sea and Tethys Ocean (Bourquin et al., 2011).

The succession of Upper Triassic deposits in the west of Paris basin comprises the Donnemarie sandstones, Chaunoy sandstones, Vert-le-Grand dolomite and Boissy sandstones. The sequence stratigraphy is characterized by a general transgressive trend during the Carnian-Toarcian cycle (Bourquin & Guillocheau, 1996), controlled by continuous creation of accommodation space, followed by a regressive trend due to an increase in sediment supply (Bourquin et al., 2002). The Chaunoy sandstones deposited in continental environments are dominated by alluvial fans with braided rivers that can evolve laterally to flood plains and shallow lakes (Bourquin et al., 1998; Eschard et al., 1998). During a later stage of decrease in accommodation space, these sandstones are affected by pedogenetic alteration with the development of dolocretes and groundwater dolomites (Spötl & Wright, 1992). The ultimate Rhaetian deposits of Boissy sandstones are also continental but show some marine influence as the transgression to Liassic intensified; they grade eastward to the marine sandstones (Novikoff et al., 2017). Across this sequence, several areas are going to be studied in the framework of MEET project in the Paris basin. The prime interest is the west of the basin but other targets will be considered later in the project.

2.1 Western edge of Paris basin

The two GCY-1 and FEX-1 boreholes, located 30km northwest and 60km northeast of Paris, respectively (Figure 1), were studied to understand the petrophysical properties of the sandstone reservoirs on the western part of the Upper Triassic depositional area. GCY-1 was drilled for geothermal purpose in 1980 and provides historical data. However, drill cores were left unfound so new data acquisition were made on FEX-1, which contains reservoir rocks analogous to that of GCY-1, as determined from well-log correlations. The present work is based on 45m drill core description, 27 oriented plugs and 28 thin sections collected from the FEX-1 core.

The sedimentary facies observed on FEX-1 core correspond to facies types defined in sedimentary systems from the Paris basin or other continental basins (Bourquin et al., 1998; Hamon & Merzeraud, 2005; Miall, 2006). They are summarized in Table 1 and representative facies are shown on Figure 2.

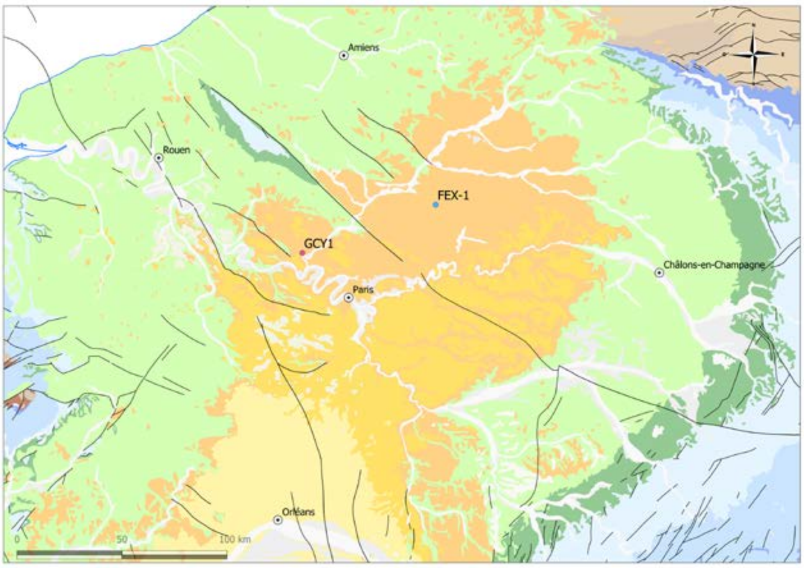


Figure 1: Location of GCY-1 and FEX-1 boreholes, overlaid on the geological map of France

Table 1: Facies description recorded on the 45m Triassic sandstones of FEX-1 core.

Facies	Grain size	Lithology	Structures	Depositional processes
Clay-rich facies				
Fr	Clay - Silt	Reddish silts with dolomitic root sleeves	Roots	Paleosoil
Fl	Clay - Silt	Reddish clays to silts with bioturbations, mud clasts (sometimes carbonaceous), and thin lenticular sandstones with reduced fronts	Laminae and/or current ripples of silt and fine sandstones	Suspension or very weak current
F	Clay	Grey-black or red clays	Massive	Decantation
Sandstone facies				
S	Medium to very-coarse-grained	Sub-angular to sub-rounded, polygenic, moderately to well-sorted, with mud clasts and matrix-supported	Massive	Gravitational deposits
Sh	Fine to medium-grained	Well-sorted	Horizontal planar-bedding	Planar laminae of low to high-flow regime
Sp	Medium to coarse-grained	Moderately to well-sorted, clast-supported	Oblique planar-bedding	Tractive current, 2D mega ripples
St	Medium to coarse-grained	Moderately to well-sorted, clast-supported	Tangential or trough bedding	Tractive current, 3D mega ripples
Conglomeratic facies				
Gmu	Gravel to pebble	Sub-angular to sub-rounded, polygenic, moderately to well-sorted, mud clasts and matrix-supported	Massive, erosional base	Gravitational deposits
Gm	Gravel to pebble	Sub-angular to sub-rounded, polygenic, moderately to well-sorted, mud clasts and clast-supported	Massive, erosional base	Lag deposits, channel base
Gp/t	Gravel to pebble	Sub-angular to sub-rounded, polygenic, moderately to well-sorted, with mud clasts and clast-supported	Rough bedding, Oblique planar-bedding or tangential bedding	Tractive current, 2D or 3D mega ripples

From the facies previously presented in Table 1 and Figure 2, depositional environments are determined using facies associations of Table 2. Associations A are characterized by fining-upward sequences with a sharp erosional surface at the base of conglomeratic facies. These deposits are typical of channel beds with tractive currents eroding alluvial plain or lacustrine sediments, as attested by the presence of mud clasts in Gm and Gp/t. It is possible to observe an evolution from proximal to distal part of the alluvial fan from A1 to A3. Associations B display coarsening-upward sequences and progressive erosional surfaces, with the occurrence of conglomeratic facies at the base and top of the sequences. The predominance of conglomeratic mass-flows allows to interpret these sequences as deltaic facies in a lacustrine domain, considering the abundance of bioturbation in the fine grained facies Fl and the decantation clays (Bourquin et al., 1998; Nemec & Steel, 1988). Fluvial systems are often associated with lacustrine deposits and it is common to observe a succession of both sediment types (Miall, 2006). Furthermore, two very distinct facies can be observed at a macroscopic scale along the FEX-1 well core: the Crouy-sur-Ourcq Fm sandstones, with rounded grains cemented by carbonates and the Feigneux Fm sandstones at the base, generally coarser than the previous ones. The analysis of the depositional environments indicates that they well correspond to those described in GCY-1 drill core reports, referring to a succession of clays, siltstones and sandstones from fluvial-lacustrine systems, with clay to silt corresponding to flood plain and decantation in lakes.

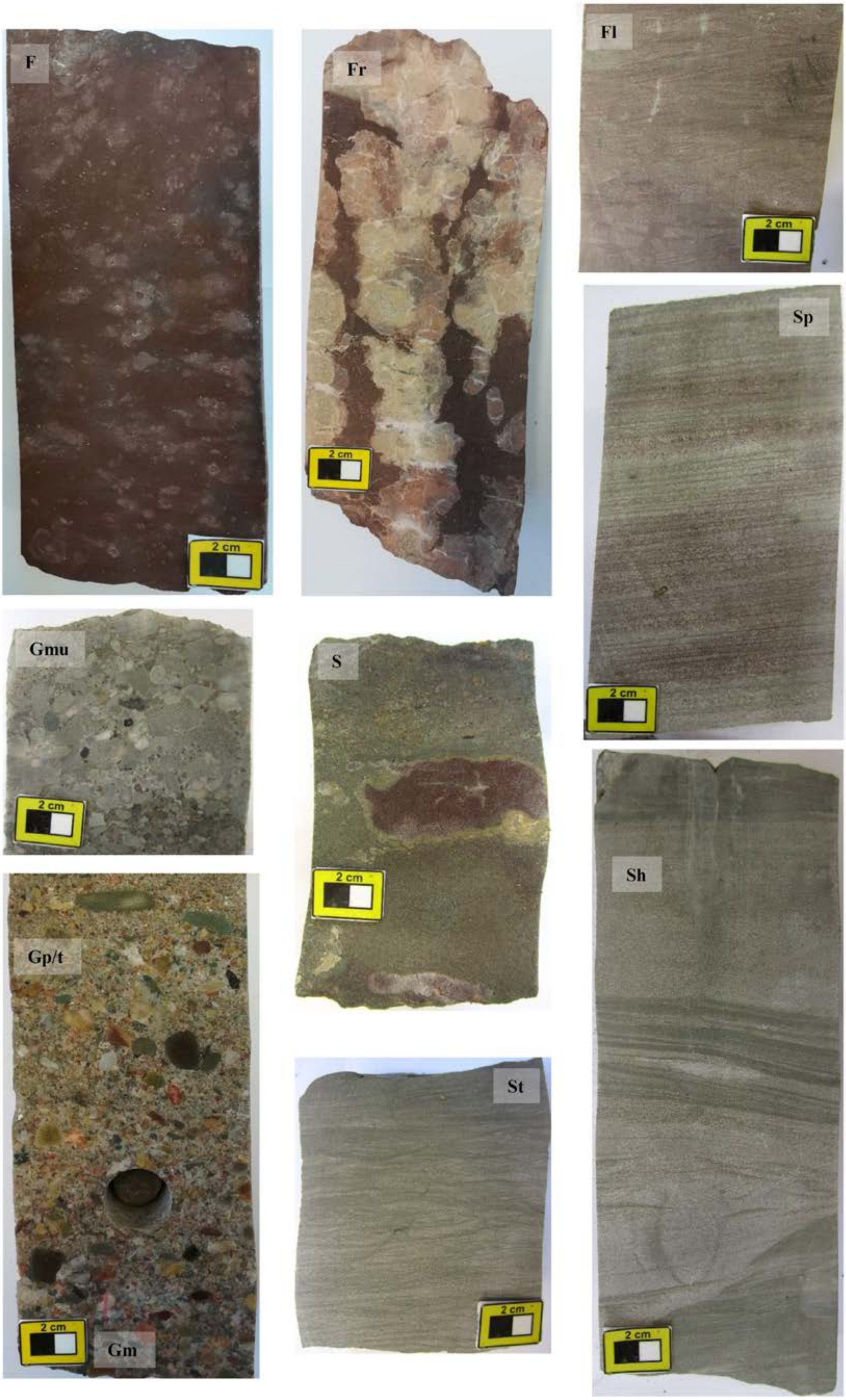


Figure 2: Facies types in the continental sandstones of FEX-1 core. F: claystone to siltstone; Fr: claystone to siltsone with roots sleeves; Fl: claystone to silstone with laminae or current ripples; S: massive sandstone; Sp: sandstone with oblique planar-bedding; Sh: sanstone with horizontal planar-bedding; St: sandstone with trough-bedding; Gmu: matrix-supported massive conglomerate; Gm: clast-supported massive conglomerat; Gp/t: conglomerate with rough bedding features.

Table 2: Facies associations interpreted from observations of FEX-1 sedimentary sequences

Facies associations A: sharp erosional surfaces, fining-upward
A1 : Gm, Gp/t, St, S *(Feigneux Fm)* **A2** : Gp/t, St, Sp *(Feigneux Fm)* **A3** : Gmu, S, St, Sp and fine intercalations of F *(Crouy-sur-Ourcq Fm)*
Facies associations B: progressive erosional surfaces, coarsening-upward
B1 : Gmu, S, Fl, St, Gp/t, Gmu, S *(Feigneux Fm)* **B2** : Gmu, S, St, Gmu *(Crouy-sur-Ourcq Fm)*

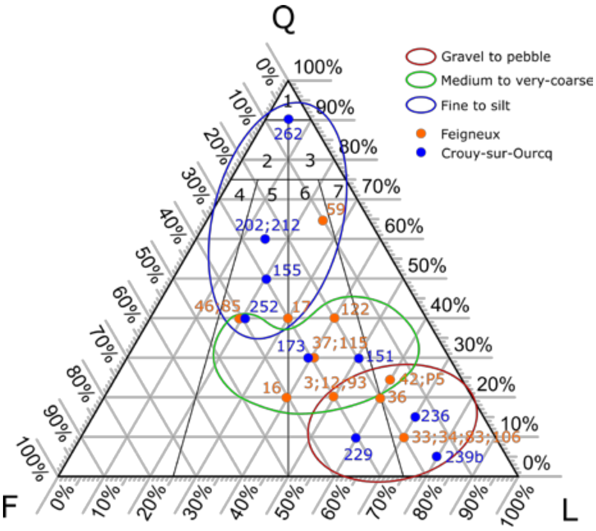


Figure 3: Sandstone composition ternary diagram with siliciclastic facies of Upper Triassic sandstones of FEX-1 core (modified after Folk, 1981). 1: quartzarenite; 2: subarkose; 3: sublithic arenite; 4: arkose; 5: lithic arkose; 6: feldspathic litharenite; 7: litharenite.

A petrographic study of the reservoir sandstones from FEX-1 well core, allowed appreciating the distribution of primary and secondary pore spaces, as well as the occurrence of later diagenetic processes such as cementation and micro-fracturing. Observations were made in plane polarized light (PPL), crossed-polarized light (XPL) and under cathodoluminescence (CL). Feigneux and Crouy-sur-Ourcq Fm are ranked as lithic arkoses, feldspathic litharenites and litharenites (areas 5 to 7 in Figure 3). The increase in the proportion of quartz is well correlated with the decrease of grain size, as represented on the Folk ternary diagram. Lithic fragments consist of polycrystalline quartz of metamorphic origin. The FEX-1 sandstone composition is very similar to the one of GCY-1, except for the source of quartz material, which is mainly magmatic in GCY-1, as mentioned in the drilling report. The Feldspar pole is much less represented, which can be explained by alteration processes (Yuan et al., 2019) along transport from the Rheno-hercynian source rocks to the north (Guillocheau et al., 2000).

The main petrographic features of FEX-1 core sandstone reservoirs are reported in Figure 4 and summarized hereafter. The most common pore spaces are intergranular (Figure 4-5), while dissolution porosity is restricted to altered K-feldspar grains and, to a minor extent, to metamorphic polycrystalline quartz grains (Figure 4-3 and Figure 4-4). Carbonate cements frequently form as pore filling phases occluding partially or totally the pores (Figure 4-1 and Figure 4-2) and one can distinguish several generations of calcites and dolomites based on their CL response (Figures 4-6 and 4-8). Four distinct diagenetic phases were recognized: 1) U-Dolomite, which is a saddle dolomite with sweeping extinction and dull red, uniform CL, fills both intergranular and dissolution pores, fractures within clasts, and also replaces some K-feldspars; it is the most abundant phase. 2) Z-Dolomite, which displays a dull red/bright red zoned CL and crystalized in pores left by matrix dissolution, is the less frequent cement. 3) O-Calcite, which displays a bright orange, uniform CL, is the second most abundant carbonate phase in FEX-1 core and participated to the total replacement of K-feldspars and other clasts. 4) NL-Calcite has a non-luminescent orange CL evolving towards bright-orange and post-dates O-Calcite cements as attested by petrographic evidences where O-Calcite surrounds quartz grains or clasts and NL-Calcite fills the remaining pores (Figure 4-6). All carbonate phases are found in both Feigneux and Crouy-sur-Ourcq Fm, though their proportion increases toward the top of the core section, where they fully occlude the pore spaces.

Saddle dolomite is known to form during mesogenesis or by hydrothermal activity (Spötl & Pitman, 2009). Two different generations of saddle dolomite cements have been distinguished in the Dogger reservoirs of the Paris basin depocenter and formed at temperatures of 65 and 95 °C, respectively during Aptian-Albian and Eocene-Oligocene times (Mangenot et al., 2018a and ; 2018b). A similar origin could be inferred for U-Dolomite observed in the FEX-1 core.

Conversely, NL-Calcite is characterized by a contrasting luminescence (Figures 4-7 and 4-8) that could result from early diagenesis (eogenesis) processes in a phreatic meteoric environment. This phase being precipitated later than O-Calcite (Figure 4-6), we hypothesize that calcite cementation most likely occurred during eogenesis.

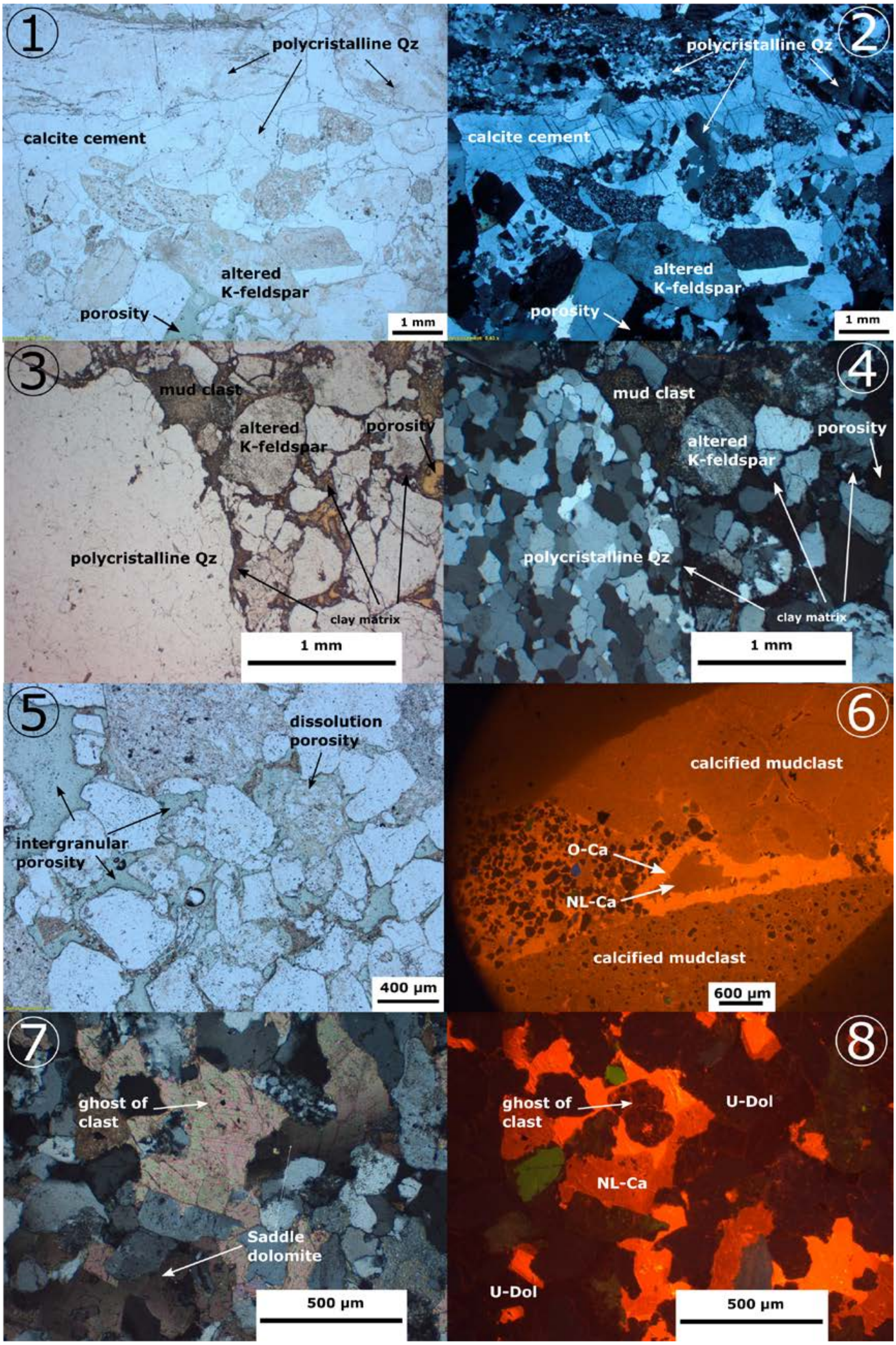
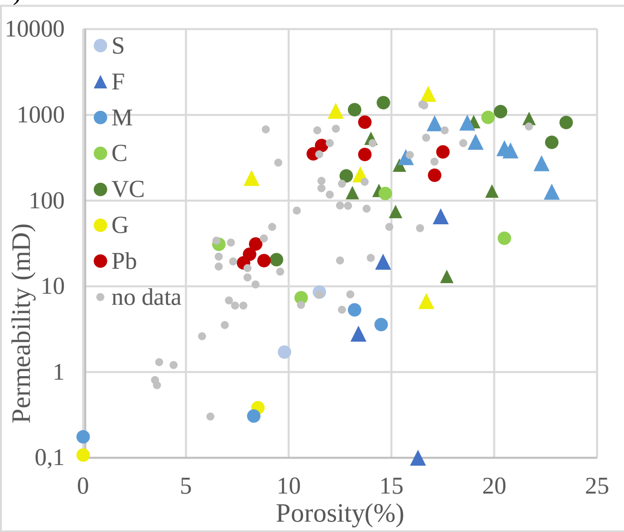


Figure 4: Petrographic images of sandstones from FEX-1 core. 1-2: composition, porosity and carbonate cementation (1: PPL, 2: XPL); 3-4: polycrystalline quartz, altered K-feldspar, mudclasts and porosity partially filled with clay material (3: PPL, 4: XPL); 5: the two different porosity types observed are intergranular porosity and dissolution porosity, the latter affecting mostly K-Feldspar and secondarily quartz grains (PPL); 6: two generations of calcite cements are recorded, orange O-Calcite and non-luminescent NL-Calcite (CL); 7-8: saddle dolomite cement with uniform very dull red color, non-luminescent calcite (NL-Calcite) and bright orange calcite (O-Calcite) in replacement of former clasts (7: XPL, 8: CL).

The textural maturity of the sandstones was qualified by optical microscopy (using a ternary diagram modified after Folk, 1981). Samples with more than 5% clay matrix are considered immature; if matrix proportion is lower than 5% and the sorting is bad, the sample is sub-mature; when the sample has less than 5% clay matrix and is well-sorted with angular to sub-angular elements, it is mature.

a)



b)

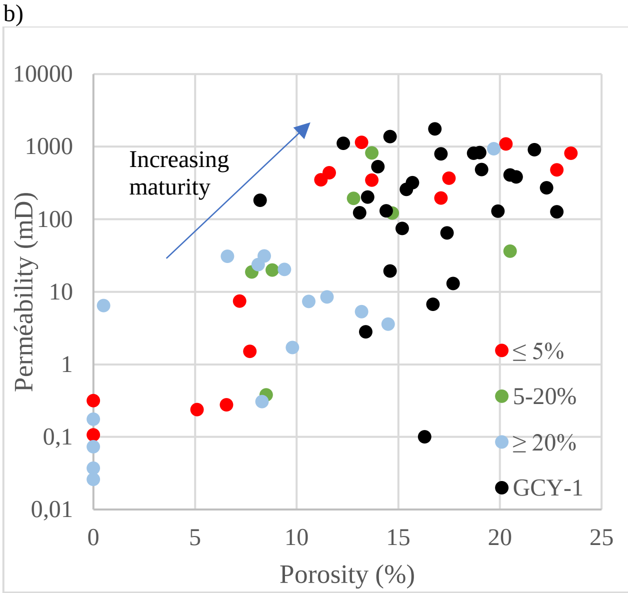


Figure 5: a) Porosity-permeability relationship of superposed FEX-1 and GCY-1 cores, versus grain size. Dots are new data from FEX-1, triangles historical data from GCY-1; red: pebble, yellow: gravel, dark green: very coarse, light green: coarse, dark blue: medium, blue: fine, light blue: silt. **b) Proportion of intergranular clays for FEX-1 and GCY-1.** Red, green and blue dots are data acquired on FEX-1, whereas black dots are from GCY-1 old data.

Finally, petrophysical properties such as porosity and permeability are measured for 27 samples in order to understand the impact of grain size, grain distribution and pore space distribution on prospective flow in Feigneux sandstones. The preliminary results in the west side margin of the Paris basin on FEX-1 well core and GCY-1 historical data combined are reported in Figure 5a. The compiled results show relevant reservoir properties for Upper Triassic sandstones at the plug scale, with 12-23 % porosity and 2-750 mD permeability in GCY-1 borehole, and 5-23 % and 4-800 mD in FEX-1 borehole. Furthermore, there are two main trends depending on grain size categories, which define different domains with more favourable reservoir quality index when sandstones are coarser. The influence of textural maturity on petrophysical trends is displayed in Figure 5b, where we see that a decrease in matrix proportion has positive influence on both permeability and porosity (the six values in the lower-left corner are from Crouy-sur-Ourcq formation that is fully cemented).

The analogue formations of FEX-1 borehole allow placing these reservoir observations in a stratigraphic approach, considering paleoenvironments and microstructures. Even though the reservoir properties of GCY-1 are very good, the vertical extensions of individual sand bodies, only 12 m when the three of them are cumulated, may not be sufficient to allow economic exploitation. Further south along the Triassic pinch-out, the thickness of individual deposits with similar facies is strongly higher (5-30 m), total thickness of 50-60 m, which would give access to a much productive resource. Moreover, due to the presence of local Permian basins of similar lithologies, the exploitable effective thickness could be increased even more.

2.2 Ardèche margin

This second part of the study concerns the Upper Triassic formations (mostly sandstones) deposited along the Ardèche margin (SE of France). One of the main goals is to provide significant insight into parameters controlling the fluid-flow properties in those successions, improving the knowledge of the relationships among petrophysics, microstructural content and geological processes.

During Triassic times, Pangea is surrounded by Tethys open-ocean to the east. When considering the paleogeography of western Tethys during Ladinian to Norian times (Dercourt et al., 2000; Scotese & Schettino, 2017), it appears that the limits of continental clastic sediments deposited along western margin of the Tethys are the analogue of Paris basin farther south. These continental environments are dominated by alluvial fans with braided rivers that can evolve laterally to flood plains or shallow lakes (Bourquin et al., 1998; Eschard et al., 1998; Spy-Anderson, 1980). Sedimentary systems are overall retrograding up to the development of pedogenetic alterations during several stacked-stages of decrease in accommodation space. Those pedogenetic alterations are marked by the development of dolocretes and palaeosoils.

Measurements of porosity and permeability properties were carried out on 70 samples, retrieved from two different outcrops that cover most of the Upper Triassic interval. The first results (Figure 6) indicate that porosity varies from 14.8 to 28.9 % and permeability from 0.014 to 7253 mD.

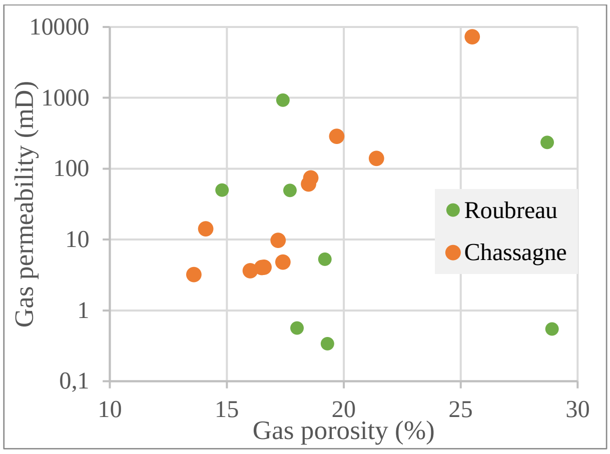


Figure 6: Porosity and permeability results of outcropping Triassic sandstones in Ardèche. Green and orange dots represent the Roubreau and Chassagne stratigraphic sections sampled in the study area.

When considering the vertically projected distribution of the porosity-permeability properties, the highest values are located below the sequence boundaries that are marked by the dolocretes and their associated features. Those preliminary results show that a possible origin of porous and permeable levels in those successions is the development of an intense dolomitisation through freshwater-related diagenesis during subaerial exposure time.

3. INVESTIGATION OF FLUID PATHWAYS IN PALEOZOIC BASEMENT OF THE PARIS AND AQUITAINE BASINS

The structural units of the basement below Paris basin are the relicts of tectonic stacking that occurred during the Variscan orogeny and were later dismantled by post-orogenic extensional and erosional processes. Due to a long history of Mesozoic sedimentation under subsidence regime, the Variscan structural features are deeply buried below the sag basin and are hardly accessible. The nature of the subcrop material is very uncertain and has been extrapolated in the Paris basin from bottom-hole geology, gravimetry, petrophysics and seismic signature of ECORS profile (Baptiste, 2016; Autran et al., 1994; Matte & Hirn, 1988). Few of the deepest boreholes have reached the basement and each well provides sparse information about the basement, most of the case a rather punctual data about the rock type. As for the Aquitaine basin, very little is known as well about the deep structures since most of deep interpretations from MARCONI seismic program especially make the basement uniform below Triassic layers (Ferrer et al., 2008; Roca et al., 2011). However, geochemical signature of basement-cover interface has been studied farther north along the Poitou High (Cathelineau et al., 2012).

This MEET project offers a unique opportunity of studying basement well cores for petrographic and petrophysical characterization of in-situ rocks. 12 deep boreholes are sampled, providing 32 samples under Paris basin and 71 samples under Aquitaine basin. Core logging reveals the evolution in the rock type from schists to gneiss and quartzite, which gives clues about the emplacement of metamorphic units. To complement these observations, the presence of main structures, fractures or cleavages provides information about potential flow pathways. Thin-sections are prepared for the analysis of detailed mineralogical characteristics under Optical Microscopy, SEM/EDS, WDS Microprobe, and coupled SEM/Raman spectroscopy. These types of analysis will deliver indications about the processes leading to mineral precipitation and possibly the nature of paleo-fluids. Finally, 64 plugged samples were collected in the drill cores in order to perform petrophysical measurements to determine the distribution of porosity/permeability and their anisotropy in the different kinds of basement. It will also serve to investigate the link between permeability anisotropy, ASM and structural patterns at micro- and macro-scales in the metamorphic rocks.

4. CONCLUSIONS

The Paris basin is the focus of an integrated study that addresses fundamental questions about deep reservoir appreciation of both Triassic sedimentary formations and its basement. These targets are lying deep under the presently exploited Dogger, with potentially much higher available heat. For the siliciclastic formations, both in-situ and outcrop analogue conditions are tested by the combination of different methodologies, such as sedimentology, petrography and petrophysics, which provides insights for the characterization of geothermal reservoir at different scales, from the stratigraphic sequence to the micro-scale. The origins of variations in petrophysical properties are closely related to internal factors as clay content and grain size distribution. Reservoirs are controlled by continental depositional systems, but also by diagenetic processes that can influence reservoir quality through cementation or dissolution phenomenon. Regarding basement formations lying under the Paris basin, the evaluation of the geothermal potential will be performed thanks to a detailed petrographic study completed by petrophysical measurements of various kinds of rock properties, as well as some of their related anisotropies in order to identify structural patterns for fluid flows. These prospective studies on deep borehole data using well cores will allow adding valuable information on two distinct geological units for the supply of hot water in the context of a growing demand in energetic needs of the Paris basin.

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