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Geothermal Exploration of Upper Triassic Deposits in the Paris Basin: Comparison of the Sedimentary Records and Petrophysical Properties between In-Situ and Analogue Site (Ardeche, France).

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ABSTRACT

The Triassic formations of the Paris Basin present a good geothermal potential with their 80-125°C reservoir temperature, making them excellent candidates for energy co-production. In order to explore such opportunity, several aspects are investigated to provide an in-depth knowledge of the Triassic formations: (1) Establish a robust sedimentological frame of the Triassic sandstone and dolomite reservoirs. (2) Highlight potential reservoirs using rock physics properties (porosity, permeability...). (3) Combine those characteristics and properties into the regional stratigraphic framework of the Paris Basin, providing a better understanding of the Triassic formations at a larger scale. The comprehension of the geothermal prospects within Triassic formations implies to evaluate the degree of horizontal and vertical connectivity between the reservoir levels, which is assessed based on a sedimentological approach. Regarding the petrophysical input, new sets of properties are characterized for key horizons that represent a good flow potential identified in hydrocarbon exploration. The porosity, permeability and P/S wave velocity are analyzed for each reservoir. Along with the study of subsurface data from the deep Paris basin, a Triassic analogue is chosen in Ardèche (France), where fluvio-lacustrine sediments have been deposited along the passive margin of the Tethys Ocean. This formation is an equivalent to the one observed in the Paris Basin, in terms of facies and textures. Its sedimentary features are described along several sections in order to realize sequence stratigraphy correlations and to analyze the rock physical properties from various lithologies along these sections. The dual settings of the Paris basin and its analogue in Ardèche provides a unique opportunity to understand the vertical stacking and horizontal continuities of clastic deposits and dolomites, for both in-situ and exposure conditions. This approach would bring insights on the capacity of Triassic deposits to bear new geothermal prospects associated with previous oil fields.

1. INTRODUCTION

One of the main objectives of the European H2020 MEET project "**M**ultidisciplinary and multi-context demonstration of EGS **E**xploration and **E**xploitation **T**echniques" is to gain further knowledge on geothermal systems embedded in sedimentary basins. It intends to explore the feasibility of electricity and/or thermal energy production using oil-producing sedimentary basins (Dalmais et al., 2020).

The sedimentary successions located at 2-3 km 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.

The purpose of this paper is two-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 the Paris Basin and field analogue in Ardèche.

2. GEOLOGICAL SETTINGS

In the Paris Basin and surrounding areas, the Triassic sediments were 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 the Paris Basin comprises the Donnemarie Sandstones, Chaunoy Sandstones, Vert-le-Grand Dolomite and Boissy Sandstones formations. 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 (Bourquin et al., 2002). The Chaunoy Sandstones are characterized by a retrogradational followed by a progradational minor cycle. This formation is dominated by alluvial fans with braided rivers that evolve laterally to floodplains and shallow lakes (Bourquin et al., 1998; Eschard et al., 1998). During the progradational trend, these sandstones are affected by pedogenetic alteration with the development of dolocretes and groundwater dolomites, i.e. the Vert-le-Grand Dolomite (Spötl & Wright, 1992). The ultimate Triassic deposits characterized by the Boissy Sandstones are also considered as continental but exhibit some marine influence at their top as the Liassic transgression intensifies; they grade eastward towards the marine Rhaetian sandstones (Novikoff et al., 2017). In the Paris Basin, across this sequence, and more specifically from Chaunoy Sandstones to Boissy Sandstones, several well sites are studied in the framework of MEET project since these formations are already oil reservoirs and bear a huge volume of trapped water.

3. MATERIAL AND METHODS

Samples described in this study come from cores from the Western Paris Basin and from several Ardèche outcrops. The cored section from the Paris basin represent a total thickness of 470 m from which 159 plug samples were collected. In Ardèche, nearly 63 plugs were taken along two sections for a total of 56 m. Laboratory measurements were performed on samples from both sites on 222 one-inch (2.54 mm) plugs drilled and oriented horizontally with respect to the bedding along the cores. All plugs were cut to an average length of 5 cm and part of each was used to make a thin section, SEM observations, and destructive experiments such as mercury injection. The considered interval shows various mineralogical compositions which have been selected during sampling.

3.1 Core/outcrop description and microfacies determination

Core logging was performed on 12 drill cores from the Western Paris Basin with care given to the facies types and sedimentary structures. Facies codes assigned to individual clastic interval are those defined in sedimentary systems from the Paris Basin or other continental basins (Bourquin et al., 1998; Miall, 2006). Half cores were very suitable for such description but most of the available cores are full-cylindrical cores, which can obliterate some figures. As for the Ardèche margin, the biggest attention was paid to the respect of thickness along the outcrop that was carried out thanks to a Jacob's stick. Lateral variations were also important to consider, while alteration of outcrops could explain the lack of sedimentary structures. Thin sections were impregnated with blue-died epoxy to visualize the pore space. Petrographic analyses (texture, composition) were conducted on both macroscopic and microscopic scale. Microfacies were analyzed on 95 thin sections from both sites. The composition of each sample was quantified by point-counting and image analysis to differentiate matrix and cement, using JmicroVision software (http://www.jmicrovision.com), with a minimum of 500 counts per thin sections and expressed in percentage. In the present study, the term micrite stands for microcrystalline calcite (crystal size below 4 µm). This term is used in a purely descriptive sense following the definition of Folk (1966) and defines both the fine-crystalline matrix of limestones and the fine-crystalline constituent of carbonate grains (skeletal or nonskeletal). The micrite content in sample is then the addition of microcrystalline matrix, micritic clasts, and micritized bioclasts when appropriate. For characterization of micrites, SEM was used. Pictures were taken at three magnifications (1) 2000X for observation of the layout of the matrix, (2) 5000X for 2-D measurement of the particles size directly on the picture (using J. Microvision software), and (3) 15,000X for the micrite morphology. Crystallometry of the micrite is defined as the median of the maximum 2-D length of 250 particles measured on SEM photomicrographs at 5000X magnification.

3.2 Petrophysical measurements

Porosity data were obtained by the triple weight method using water and which gives access only to the volume of connected pores in the samples. Mercury injection porosimetry was performed using an Autopore IV 9500 porosimeter. It can generate pressures from 3.10^{-3} to 200 MPa, providing access to pores with throat diameters of 0.03 µm to 360µm. The analytical accuracy ranges from ±0.001 µm to ±0.01µm.

The gas permeability measurements were performed with a Hassler cell using nitrogen. During the measurements the flow was laminar. Permeability tests were performed with a steady state permeameter (lower limit of 10^{-3} mD) and made at a confining pressure of 3 MPa. Some additional measurements on key samples have been made using a high confining pressure vessel (up to 70 MPa with a measurement every 7 MPa). The data have been systematically corrected of the Klinkenberg slip effect.

The experimental device for the acoustic measurements includes a set of ultrasonic transducers with 0.5MHz central frequency for both P and S waves that propagate along the plug axis. Ultrasonic waves are generated by a pulser (Panametrics 5058) with a frequency in the megahertz range. A mild contact force was applied during the measurement, and a soft rubbermembrane with coupling gel was used to maintain a good contact between transducers and core plugs. We measured the time of flight for acoustic waves traveling from the transmitter to the receiver through our samples first in dry and second in water-saturated conditions, under ambient temperature and pressure. The accuracy of velocity measurements for our data set is ± 1%.

4. RESULTS

The sedimentological data are highly variable in the 12 studied boreholes and necessitate being synthetized for clarity. The presented results are thus an attempt to show first order variations of sedimentary facies in order to fix important features of this complex sedimentary organization. In a similar manner, sampling is not intended to be fully representative of the lithology variations, but bring the material to study parametric laws between sedimentary features such as grain size, and physical parameters of rocks determined in laboratory.

4.1 Sedimentology

Upper Triassic continental deposits of the Paris Basin

The sedimentary record of the Upper Triassic deposits in the Western Paris Basin is mostly controlled by alluvial fans deposits and the lake level variations (Bourquin et al., 2002). In the overall sequence, basin infill is characterized by sandstone and conglomerate deposits with erosional surface and lags at the base, alternating with bioturbated sandstone beds showing current ripples, and finely laminated clay-silt beds associated or not with bioturbations.

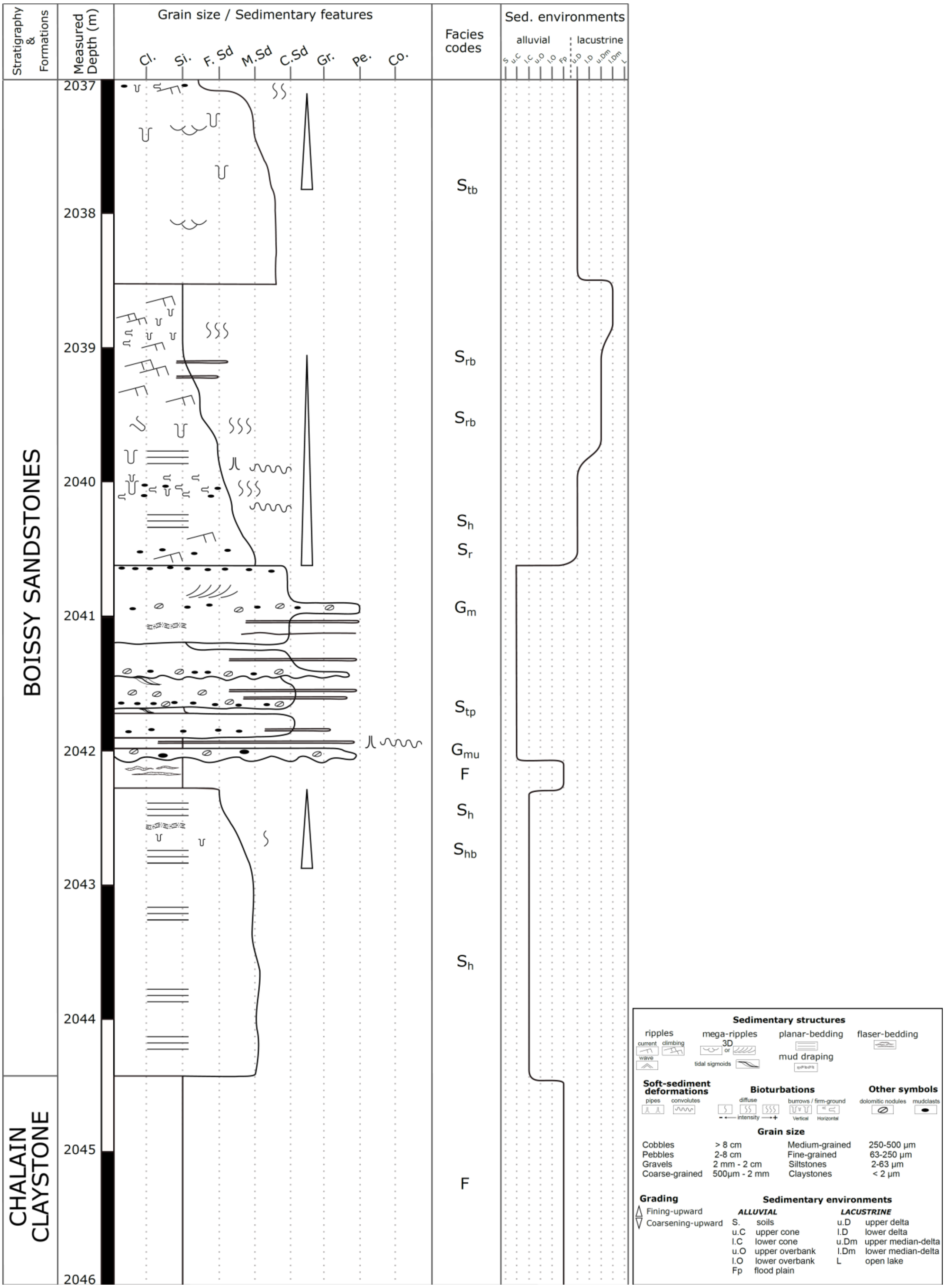

Figure 1: Sedimentological section of the Boissy Sandstones reservoir in the western Paris Basin. Facies codes indicated are used to interpret the grain size evolution and associated sedimentary structures in terms of depositional environments.

In the Paris Basin, even though sedimentary deposits are variable from well to well, some common features can be summarized and the general architecture of the sedimentary successions can be described as following, with increasing depth:

- The Boissy Sandstones are composed of stacked units of several meters each that can be either massive, which correspond to debris-flow discharge, or well-structured with parallel-bedding and 2D or 3D megaripples, and then current ripples at the top (Figure 1).
- The Vert-le-Grand Dolomite is composed of vuggy dolomites that are partially or totally replacing the original siliciclastic deposit. Dolomitization can affect all kind of lithologies as a secondary diagenetic feature. The dolostones appear either massive or nodular when they are associated with root sleeve. The dolomitization may be effective in the Chaunoy Sandstones at varying thickness depending on the percolation power.
- The Chaunoy Sanstones are mainly composed of a succession of massive conglomerates to sandstones intercalated with 2D-3D megaripples, with some dolomite paleosoil developments where roots are emplaced in fine-grained sediments.

The evolution curve of sedimentary environments is determined from the grain size evolution and facies associations. In consequence, the continental depositional profile (Figure 1) define a particular depositional environment between paleosoils and open lake.

Triassic sequence of Ardèche analogue

In the Ardèche paleomargin, a sequence from the Upper Triassic is surveyed. The “Ensemble gréso-dolomitique gris” and “Formation bariolée d’Ucel” that stand for facies analogues of the siliciclastic deposits of the Paris Basin described above, are observed along the Chassagne outcrop (Figure 2). This section shows part of the features that are commonly seen on cores with a vertical stack of sandstone to conglomerate beds and paleosoils. What makes these outcrops significantly valuable is the possibility to observe the evolution of deposition in space, with lateral relationships between sand bodies and paleosoil developments. The orientation of the outcrop (NNW-SSE) allows observing the longitudinal geometry of the sandstone bodies. The erosional bases of massive beds are clear, as the interbedding of sandstones with paleosoils, or dolomitization of original sedimentary material. Dolocretes are well developed and are associated with sequence boundaries at the top of debris-flow discharge in the lower part of the outcrop in particular. They often obliterate the primary sedimentary features, a phenomenon attested by the presence of clastic relicts in the dolostones. From the base to top of the sequence, the thickness of paleosoils increases while the thickness of sandstone beds decreases. Indeed, the transition between the two formations is observed: the “Ensemble gréso-dolomitique gris” is marked by thick sandstone and conglomerate beds, frequently fining-upward, separated by thin paleosoil developments, whereas the “Formation bariolée d’Ucel” shows dominant thick paleosoils separated by thin conglomeratic beds (Figure 3).

Figure 2: Vertical stacking and lateral continuities of sandstone bodies and paleosoils (in red) at the Chassagne locality: lower picture corresponds to the 10-15m interval on the sedimentological section (Figure 3) whereas the upper picture corresponds to the section around 30m (Figure 3). Jacob’s staff measures 1.80m.

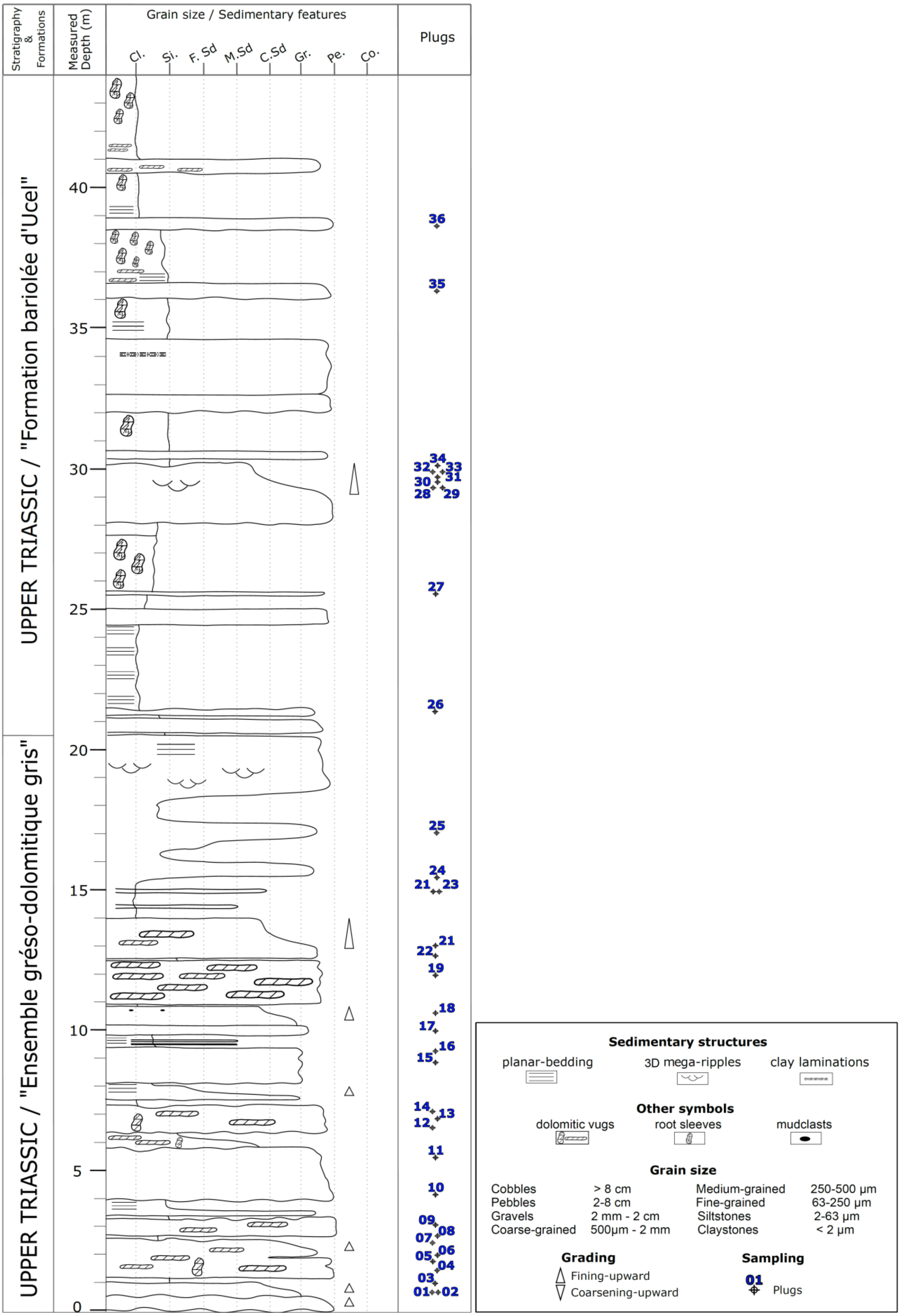

Figure 3: Sedimentological section of the Chassagne locality (Ardèche), displaying the two formations of Upper Triassic and the emplacement of plug samples for petrophysical measurements.

4.2 Petrophysics

Porosity displays a wide range of values from 2.12% to 16.2% in the Paris Basin dataset and from 4% to 22.5% in the Ardèche analogue (Figures 4 to Figure 7). Micropores are observed in both micritized grains and matrix but are scarce. Macropores, on the other hand, are dominant throughout the formation, except in the palaeosoil levels.

Permeabilities range from 0.09 mD to 2700 mD in the Paris Basin, and up to 10^4 mD in the Ardèche margin, with a median value of 0.78 and 0.408 mD, respectively. The measured permeability ranges over five orders of magnitude. Figures 6 and 7 show a large superposition of the ϕ-k properties regarding the texture, cements and grain size, even though the coarser samples tend to have the highest permeability for a given porosity. One interesting observation is that the permeability of the fine-grained samples is almost constant and does not show any clear porosity dependence.

Measured dry P-wave velocities range from 1100 to 6800 m/s in the Paris Basin and from 1819 to 5400 m/s in the Ardèche margin samples (Figures 5 and 7). Primary control on the acoustic velocity is exerted by total porosity for rocks with similar mineralogical content: P-wave velocity decreases with increasing porosity. Here, our data almost display a linear trend rather than the usual concave upward evolution (Kenter et al., 2002). Moreover, velocity variation at a given porosity is wide and exceeds 2500 m/s. Notice that this almost linear relationship between acoustic velocity and porosity, as well as a low dispersion of the data, has also been found in other studies on similar rocks (Regnet et al., 2018). When samples are discriminated by their textural properties on a ϕ/Vp crossplot, the fine-grained samples display a lower velocity at a given porosity respect to the coarse-grained samples. This is well-observed on the Paris Basin data, but more cumbersome in the Ardèche samples, where ϕ/Vp evolution is characterized by a more cloudy distribution.

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.

Upper Triassic continental deposits of Paris Basin

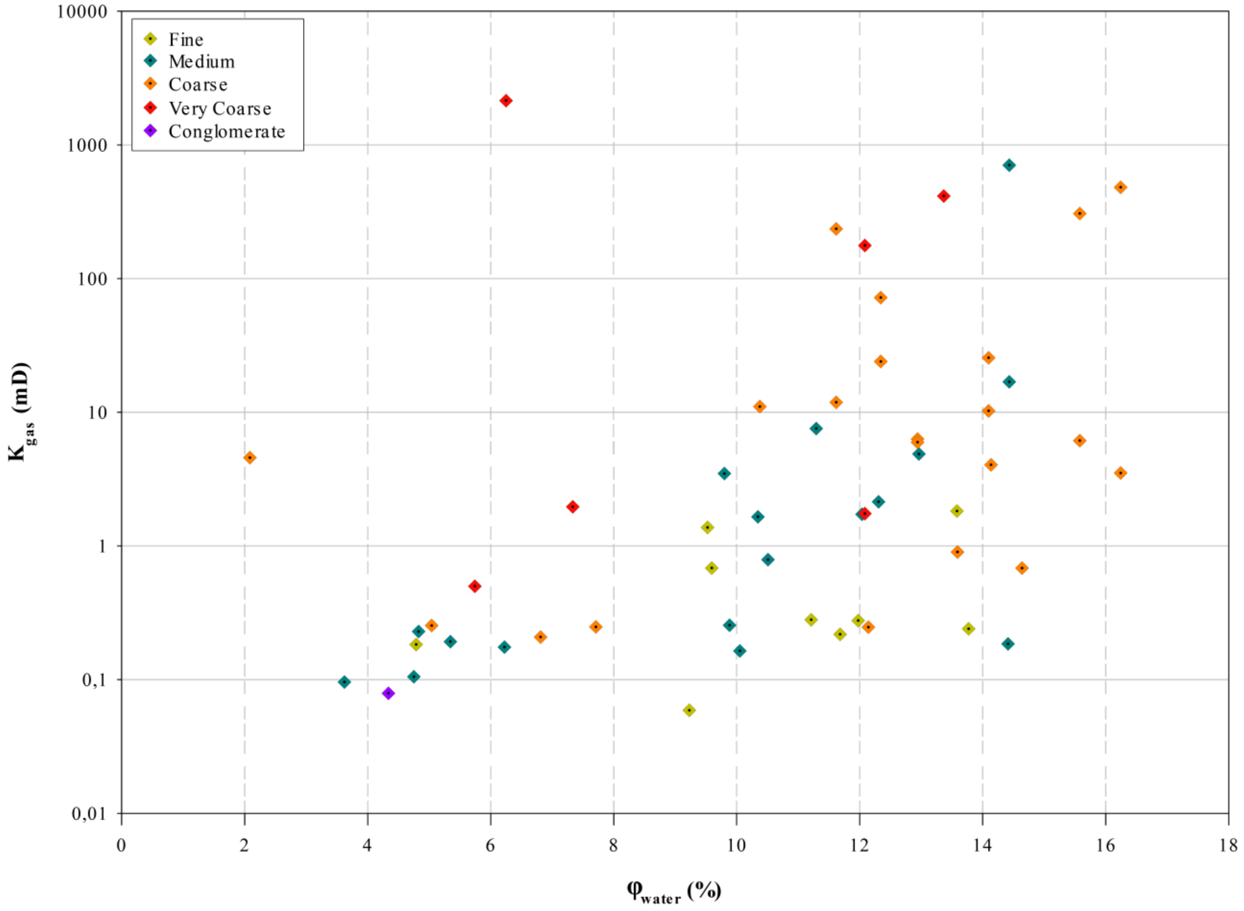

Figure 4: Water porosity-gas permeability measurements on 50 samples from the Paris Basin, with grain size criteria represented

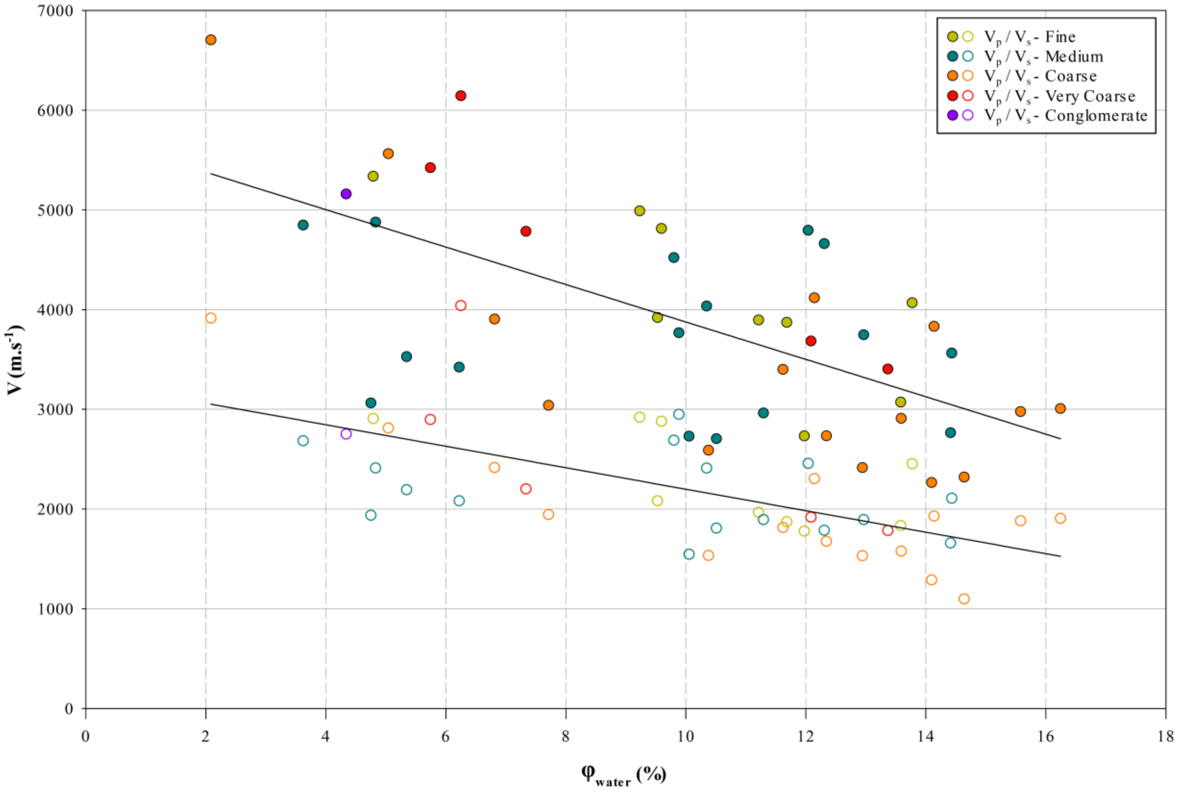

Figure 5: Water porosity / acoustic velocities of the Paris Basin. Full circles show V_P and empty ones are V_S. Grain size criteria is drawn with the same color for either V_P or V_S.

Ardeche margin analogue

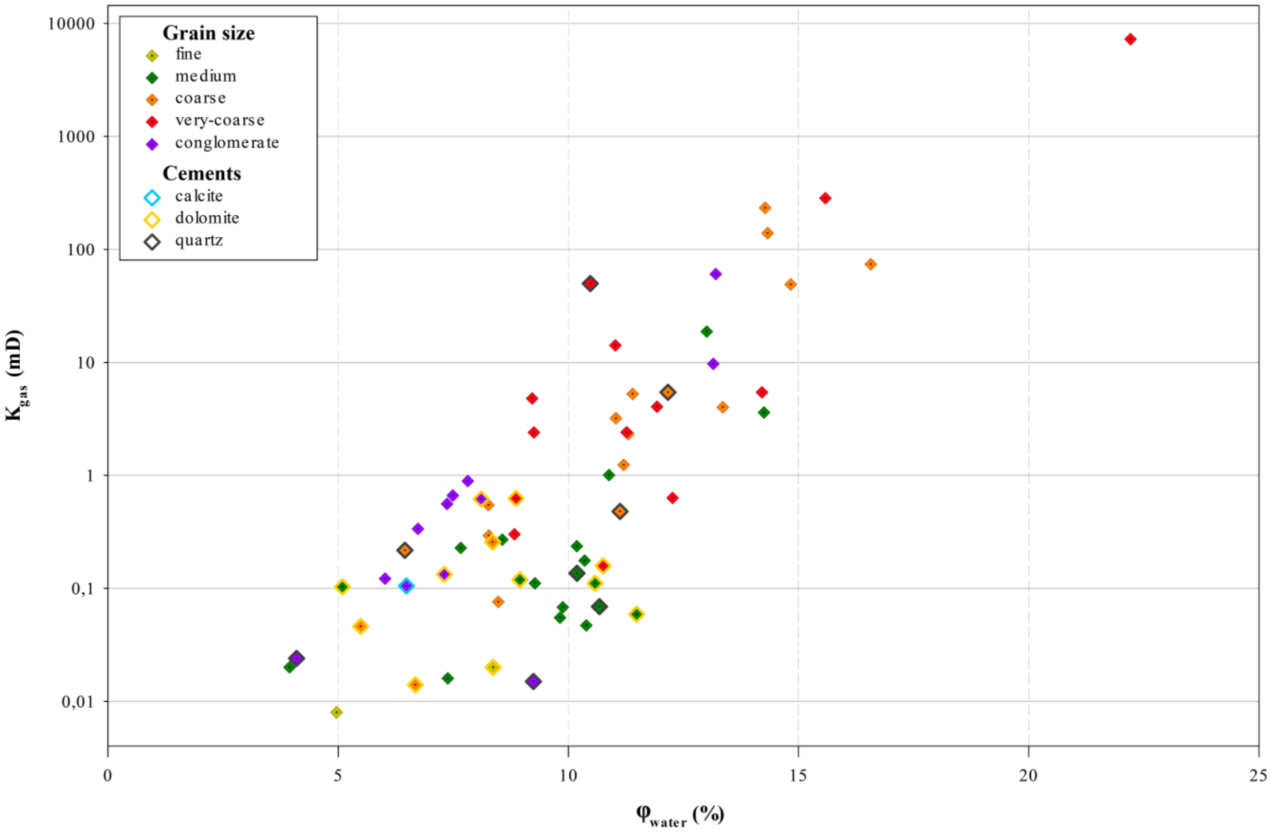

Figure 6: Water porosity / gas permeability measurements of Ardèche outcrops. Grain size is shown from fine to conglomerate. Macroscopic cements are represented with surrounding diamonds (blue: calcite; yellow: dolomite; dark: quartz)

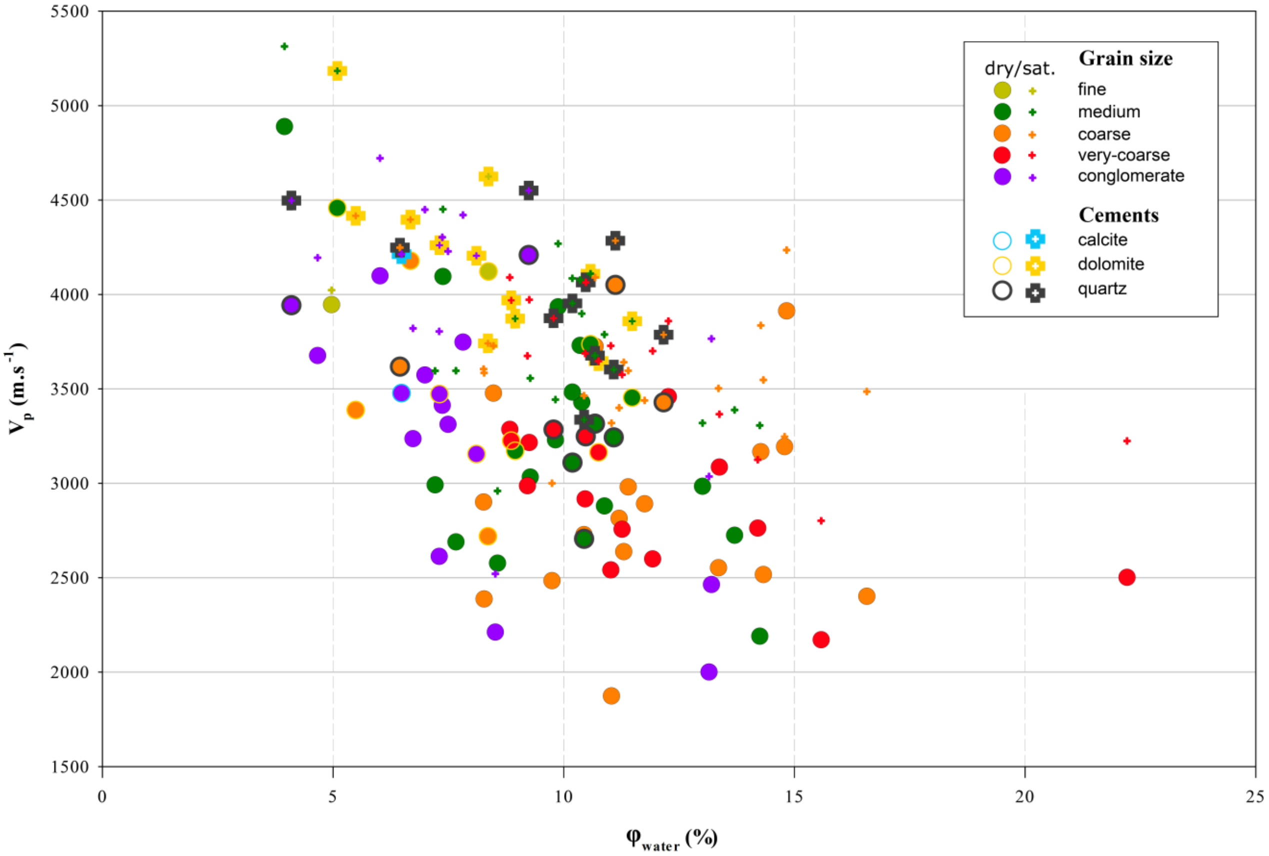

Figure 7: Water porosity / acoustic P-wave velocities of Ardèche outcrops. Grain size criteria is represented with the same color for $V_p$dry and $V_p$sat, whereas macroscopic cement are shown with surrounding circle or cross (blue: calcite; yellow: dolomite; dark: quartz)

5. DISCUSSION

The sandstone and dolomite reservoirs of the Paris Basin show contrasting depositional features that are the consequence of mixed fluvial-lacustrine paleoenvironments. Alluvial fans and braided rivers supply sediments that accumulate along the border of the Paris Basin and the Ardèche margin. The lateral and vertical distribution of sedimentary bodies is highly dependent on the geometry of the emerged domain but also on the sequential evolution of deposits controlled by first order processes such as climate, tectonics and eustatism (Bourquin et al., 1997; Poli, 1997). The vertical stacking of siliciclastic reservoirs in the Paris Basin and the lateral breakdown of individual sandstone bodies in the Ardèche analogue are assessed and show a strong sedimentary heterogeneity due to depositional conditions. In addition, secondary diagenetic features such as dolomitic cements were developed and could mask the sedimentary structures and granulometric evidences (Spötl et al., 1993). This is clearly the case in both Paris Basin and Ardèche settings. Indeed, the paleosoils identified in the field perfectly match the tubular dolomitic features observed on cores, structures that have a distinct origin than those of massive dolomites resulting from groundwater fluctuations and associated precipitations (Colson & Cojan, 1996; Spy-Anderson, 1980; Tucker et al., 1990).

Permeability and acoustic wave properties indicate that the grain size and degree of cementation influences the favorability of reservoirs. The coarse and very-coarse-grained sandstones appear to be the most effective grain classes for fluid flow. The different kinds of cements all have negative effect on the reservoir rocks, decreasing permeability and increasing Vp. However, one of the most productive reservoirs at macroscopic scale is embedded within dolomites of diagenetic origin, which is not clearly confirmed by small-scale petrophysical measurements. Both dolomites and sandy dolomites of the Paris Basin and the Ardèche margin record very low permeabilities and high Vp values. This may be explained by the well-expressed secondary porosity of the vuggy dolomites that could be a consequence of micro-karst as identified on analogue rock types (Colson et al., 1998) or volume reduction during dolomitization (Tucker et al., 1990). Concerning the Boissy Sandstones the sampling is not dense enough to appreciate the potential of porous layers in relationship with grain size or facies type. On the contrary, the Chaunoy Sandstones could be the subject of such a characterization, since they display a wide range of grain sizes, facies types and degrees of dolomitization.

Once the sedimentological model is achieved over the whole geothermal field of Triassic sandstones for the fluvio-lacustrine system, a large dataset is produced for each petrophysical method and is linked to facies types, grain size and cementation phases. This is performed in accordance with vertical and lateral sedimentary architecture, in order to predict the best horizons and effective thickness that could be exploited for a geothermal project. This work is achieved in parallel of a detailed petrographical study in order to precise the diagenetic history of the sandstones and to characterize the occurrence of the Vert-le-Grand Dolomite in time and space. The petrophysical results are then reinterpreted in light of this complementary work.

6. CONCLUSION

The geothermal potential of Upper Triassic continental siliciclastic deposits of the Paris Basin is investigated by means of a combined sedimentological and petrophysical study, aiming to identify the favorable layers for fluid circulation in this heterogeneous depositional environment. Facies types are identified on cores, which allow reconstructing the vertical evolution of paleoenvironments along the alluvial-lacustrine profile. The 3D architecture is apprehended on targeted outcrops of the Ardèche analogue and confirms that sedimentary features are equivalent to in-situ conditions of the Paris Basin. The rock physics data of both geological settings show that coarse to very-coarse-grained classes are more indicated for fluid flow with high permeabilities and low Vp values. The P-wave velocities are controlled by total porosity and presence of cements, whereas permeability is mostly guided by classes of grain size and cements as well. The distribution of the porosity-permeability properties on vertical sections suggests that highest values are associated with sequence boundaries identified by the occurrence of dolocretes, which could mean that promising levels for geothermal applications are associated with intense dolomitisation through freshwater-related diagenesis during subaerial exposure time. Further effort is engaged on the possible link between petrophysics and facies types, on stratigraphic correlations at the scale of the geothermal field, and on a microtextural analysis of diagenetic features of the dolomitic reservoirs to complement the present approach.

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REFERENCES

Bourquin, S., Rigollet, C., & Bourges, P. (1998). High-resolution sequence stratigraphy of an alluvial fan-fan delta environment: stratigraphic and geodynamic implications - An example from the Keuper Chaunoy Sandstones, Paris Basin. *Sedimentary Geology*, *121*(3–4), 207–237.

Bourquin, S., Robin, C., Guillocheau, F., & Gaulier, J.-M. (2002). Three-dimensional accommodation analysis of the Keuper of the Paris Basin: discrimination between tectonics, eustasy and sediment supply in the stratigraphic record. *Marine and Petroleum Geology*, *19*(4), 469–498.

Bourquin, S., Vairon, J., & Le Strat, P. (1997). Three-dimensional evolution of the Keuper of the Paris basin based on detailed isopach maps of the stratigraphic cycles: tectonic influences. *Geologische Rundschau*, *86*(3), 670–685.

Colson, J., & Cojan, I. (1996). Groundwater dolocretes in a lake-marginal environment: an alternative model for dolocrete formation in continental settings (Danian of the Provence Basin, France). *Sedimentology*, *43*(1), 175–188.

Colson, J., Cojan, I., & Thiry, M. (1998). *A hydrological model for palygorskite formation in the Danian continental facies of the Provence Basin (France). Clay Minerals* (Vol. 33).

Folk, R. L. (1966), A review of grain-size parameters, Sedimentology, 6, 73–93.

Kenter, J. A. M., F. S. Anselmetti, P. H. Kramer, H. Westphal, and M. G. M. Vandamme (2002), Acoustic properties of "Young" carbonate rocks,

Miall, A. D. (2006). *The geology of fluvial deposits : sedimentary facies, basin analysis, and petroleum geology*. Berlin: Springer.

Poli, E. (1997). *Stratigraphie séquentielle haute-résolution, modèles de dépôt et géométrie 2D-3D des séquences triasiques de la marge téthysienne ardéchoise*. Université de Bourgogne.

Regnet, J.B., Fortin, J., Nicolas, A., Pellerin, M., Guéguen, Y., 2018. Elastic properties of continental carbonates: from controlling factors to an applicable model for acousticvelocity predictions. Geophysics 84 (1). https://doi.org/10.1190/GEO2017-0344.1. (january-february 2019); P. 1–14, 15 Figs., 1 Table.

Spötl, C., Matter, A., & Brevart, O. (1993). Diagenesis and pore water evolution in the Keuper Reservoir, Paris Basin (France). *Journal of Sedimentary Research*, *63*(5), 909–928.

Spy-Anderson, F.-L. (1980). *La bordure vivaro-cévenole au Trias dans la région des Vans (Ardèche) : histoire tectono-sédimentaire, évolution diagénétique d'encroûtements dolomitiques de piémonts et de plaine alluviale*. PhD Université Claude Bernard (Lyon 1).

Tucker, M., Wright, V. P., & Dickson, J. A. D. (1990). *Carbonate Sedimentology.*