



# DELIVERABLE D3.6

## SUMMARY OF PETROPHYSICAL ANALYSIS

### WP3: UPSCALING OF POWER PRODUCTION AND OPTIMIZED OPERATION OF EGS PLANT

Contractual delivery date:	M30
Actual delivery date:	M33

#### PROJECT INFORMATION

Grant Agreement n°	792037
Dates	1 <sup>st</sup> May 2018 – 31 October 2021

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## DOCUMENT INFORMATION

Version	VF	Dissemination level	PU
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## DOCUMENT HISTORY

Version	Date	Modifications	Authors
V1	22/01/2021	First version submitted to coordinators	CÉDRIC BAILLY / CYU XAVIER SENGELEN / CYU
V2	27/01/2021	Corrected version with comments from coordinators and partners	CÉDRIC BAILLY / CYU XAVIER SENGELEN / CYU
VF	30/01/2021	Final version	ALBERT GENTER (ESG) & JEAN HERISSON (AYMING)

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## PUBLIC SUMMARY

This scientific report gathers a detailed summary of the activities lead by the GEC Laboratory (CY Cergy-Paris Université, France) and associated partners over the course of 2 years in the frame of the H2020 MEET Project. We propose a global integrative workflow that allows us to (i) precisely characterize the multi-scale geological heterogeneities of a Triassic sedimentary reservoir from the Paris Basin, and (ii) to highlight the governing controls of those heterogeneities on the spatial distribution of petrophysical properties.

This research project may provide a global concept on geology-based modeling. It will also help us to reduce uncertainties linked to geothermal energy management within heterogeneous sedimentary aquifers.



## 1 EXECUTIVE SUMMARY

### 1.1 DESCRIPTION OF THE DELIVERABLE CONTENT AND PURPOSE

Enhancing petroleum sedimentary basins for electricity and/or thermal production is thought to be a crucial progress for future developments in geothermal energy and is also one of the main objectives of the MEET project in the frame of WP4. The Upper Triassic formations (i.e. Keuper) within the western Paris Basin are exploited for their sedimentary-bearing hydrocarbon reservoirs and present a good geothermal potential with their 75-90°C bottom-hole temperature, making them excellent candidates for energy co-production or stand-alone new geothermal projects. In the Paris basin, most geothermal projects depend on the Dogger reservoir resource, however there are concerns about the remaining geothermal potential of this geological level due to the density of existing geothermal doublets; hence the interest in the deeper Triassic geothermal resource. Regarding co-production, the opportunity arises from the active petroleum wells producing a considerable amount of hot water (~99 % of total fluid) that is reinjected in the reservoir. Finally, one can also think in terms of conversion of oil wells coming to their end of life or already abandoned into geothermal energy producers. Many examples are currently developed worldwide (e.g. Cheng et al. 2013, Cheng et al. 2016, Røksland et al. 2017, Cheng et al. 2019).

In order to explore such opportunity in the Paris basin formations, several aspects are investigated to provide an in-depth knowledge of the Upper Triassic sedimentary porous formations:

- (1) Building a highly constrained sedimentological framework and diagenetic history of the Triassic sandstone and dolomite reservoirs,
- (2) Carry-out a detailed petrophysical study to characterize reservoir properties (porosity, permeability)
- (3) Integrate points (1) & (2) into the regional stratigraphic framework of the Paris Basin, providing a better understanding of the Upper Triassic formations on a larger scale.

The prospects of Vert-le-Grand (Essonne, France) and its associated reservoirs, the so-called Chaunoy Sandstones and Vert-le-Grand Dolomites were selected for the study. They are well documented, and several cored sections are available, which provide a complete vertical succession of sedimentary sequences.

The recognition of stratigraphic cycles at different scale (from reservoir to basin) is necessary to understand the reservoir architecture and evolution through time. Our goal here is to clarify/clear up the position of the different reservoir units within the Upper Triassic cycles from sedimentary architecture data, and the succession of depositional environments (mostly continental and driven by geodynamic/climatic factors), in the context of the post-Variscan collapse of remnant reliefs.

The comprehension of the geothermal prospects within Upper Triassic formations requires assessing the degree of horizontal and vertical connectivity between the reservoir units. To

achieve this, the study is built around several integrative and consecutive steps. In a first step, the sandstone/conglomerate bodies and dolomite levels are characterized by their facies from a core study and their facies association. In a second step, the electrofacies characterization is realized by a well-log analysis to determine precisely the facies/electrofacies relationship. In a third step, the combined facies and electrofacies analysis leads to define the vertical evolution of depositional environment for each well. In a fourth step, the correlations of the depositional environment evolution, at different scales (from the field to the basin), allows to define stratigraphic sequences for the Chaunoy Formation, including sandstone and dolomite bodies. The post-depositional processes of the sandstones are characterized separately. Indeed, diagenetic processes like silicification or dolomitization of sandstones induced by soil formation and fluid circulations in vadose or aquifer zones are studied through sedimentary petrography (optical microscopy, cathodoluminescence), in order to evaluate their impacts on reservoir quality.

While performing a joint approach combining sequence stratigraphy and sedimentology, an original petrophysical approach is proposed and focuses on the analysis of favourable facies/electrofacies for reservoir quality. Regarding the petrophysical input, the effort is concentrated on the characterization of new sets of properties for key horizons that represent a good flow potential identified in hydrocarbon exploration. The porosity and permeability properties are analysed for sandstones and dolomite matrix-dominated reservoirs. To further extend the analysis, another part of the study consists in a comparison between fine measurements at plug scale and well-log signals. This allows to perform fine correlation of reservoir layers and facies types along the cores, but also to extend this approach to the un-cored sections.

## **1.2 BRIEF DESCRIPTION OF THE STATE OF THE ART AND THE INNOVATION BREAKTHROUGHS**

As part of the energy transition, scientists may focus on the geothermal potential of the Earth as a prominent and promising renewable energy to reduce the emission of greenhouse gases (Fridleifsson, 2001; Simmons, 2021). Various geological contexts may be investigated, using several technologies such as enhanced geothermal systems fluids (*e.g.* Olasolo et al., 2016, Ledésert & Hébert, 2020); geothermal co-production of oil and heat using existing wells (Wigh and Benett, 2015); and exploitation of depleted oil reservoirs for producing and storing heat (Dickinson et al., 2009). In this context, European sedimentary basins may be considered as very interesting targets for both heat production and storage (Hurter & Haenel, 2002). Nevertheless, several key challenges need to be handled for ensuring a suitable management of geothermal energy within heterogeneous sedimentary reservoirs (HSR).

A major issue concerns the understanding of upscaling of reservoir properties (*i.e.* porosity and permeability from sample scale to reservoir scale). It is addressed since decades by geoscientists, gathering numerous academic and industrial researchers focusing on several fields such as

geology, geophysics, hydrogeology and modeling (*e.g.* Miall, 1996; Renard & Marsily, 1996; Klingbeil et al., 1999; Ritzi et al., 2003; Marsily et al., 2005; Nordahl & Ringrose, 2008; Ringrose & Bentley, 2015; Bailly et al., 2019a). Yet, most of these studies rely on the fact that we have to take into account the multi-scale geological heterogeneities, namely the structural framework, the sedimentary architecture and the diagenetic overprint that control the porous network. With that in mind, we can build 3D static reservoir models using geostatistics, gathering petrophysical properties of rocks based on well-constrained conceptual geological models. Such an approach is the key for understanding and forecasting the behavior of fluid flow within a geological reservoir (*e.g.* Eschard et al., 1998). Nevertheless, concerning the geothermal energy management, even though modelers take into account the large-scale sedimentary architecture and the structural setting (*e.g.* Stricker et al., 2020), they do not consider high resolution heterogeneities (*i.e.* microstructure evolution due to sedimentology and diagenesis, lateral continuity of sedimentary units...) that may considerably affect compartmentalization of HSR and thus the heat transfer. Indeed, recent studies focusing on hot sedimentary aquifers insist on the fact that we need to fully understand the sedimentary architecture of the targeted reservoirs to estimate all the geological risks for ensuring a safe exploitation of geothermal energy (*e.g.* Willems et al., 2017). Furthermore, the spatial variability of the porosity and permeability considerably affects the hydraulic connectivity and thus the thermal dispersion (thermal diffusion and convection), an important coefficient that has to be studied if one wants to reduce the uncertainties considering the spreading of heat in aquifers (Ferguson, 2007; Hidalgo et al. 2009, Molina-Giraldo et al., 2011). In order to tackle these key issues, we need to characterize the multi-scale heterogeneities controlling fluid flow and heat transfer. Following the conceptual scales of Haldorsen & Lake (1984), we thus need to take into account the microscopic scale (*i.e.* pore scale depending on primary microstructure with diagenetic overprint), the macroscopic scale (*i.e.* sample scale related to lithofacies), the megascopic scale (*i.e.* size of model gridblocks related to facies association) and the gigascopic scale (*i.e.* formation scale related to genetic stratigraphy). To do so, we investigated a Triassic HSR from the Paris basin, showing varying lithologies overprinted by several diagenetic processes.

We propose a new and novel approach for characterizing the reservoir compartmentalization of this Triassic HSR by investigating the whole geological scales defined by Haldorsen & Lake (1984), from microscopic scale to gigascopic scale. The originality of our work lives in the fact that we integrate the small-scale heterogeneities (microtexture and diagenetic overprint) within a well-constrained sedimentary architecture (high-resolution stratigraphic framework). Such an innovative approach allows us to accurately i) understand the controlling factors of petrophysical properties at microscopic scale and ii) define their spatial evolution at gigascopic scale based on a detailed study of macroscopic/megascopic heterogeneities. Therefore, our approach can potentially serve as a benchmark workflow for future purposes focused on the geothermal development within HSR.



### 1.3 CORRECTIVE ACTION

The due date of this deliverable was first set to M30 (31<sup>st</sup> October 2020). As French universities were closed during the first lockdown of Covid-19 pandemic (17<sup>th</sup> March 2020 to 11<sup>th</sup> May 2020), which severely restrained the work that should have been performed in the laboratories, CY Cergy Paris University partner is releasing this deliverable at M33 (31<sup>st</sup> of January 2021).

This deliverable is officially integrated into the WP3 “Upscaling of power production and optimized operation of EGS plants” but it refers to the WP4 “Enhancing petroleum sedimentary basins for geothermal electricity and thermal power production”. The reason of this discrepancy can be traced back to the first times of MEET project, when WP1 “Ethics requirements” was added. Consequently, all deliverables were modified, but the ID number of this deliverable was not modified to D4.X.

### 1.4 IPR ISSUES

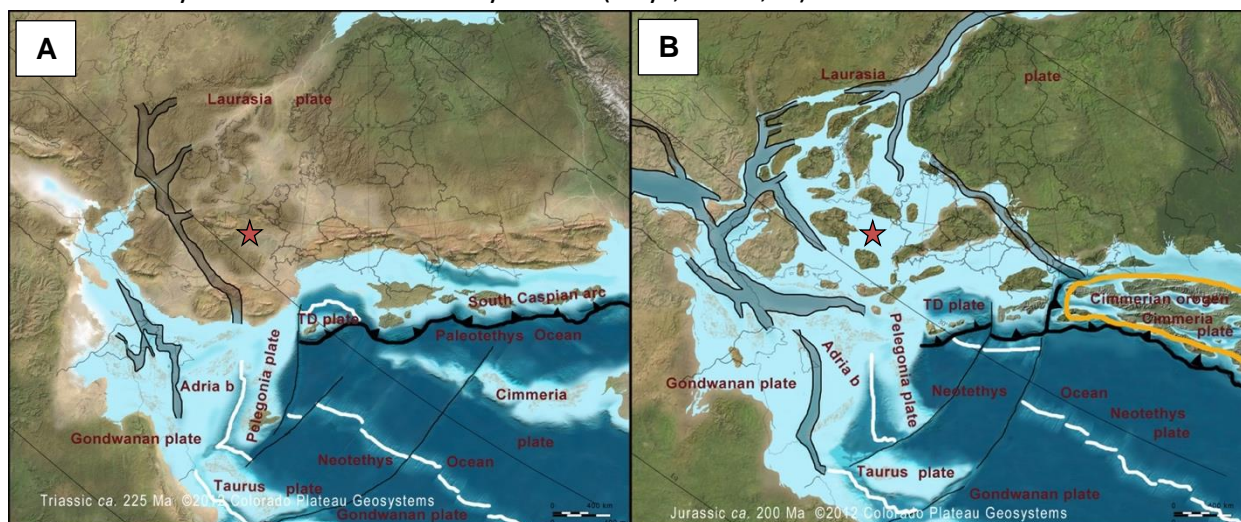
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## 2 SUMMARY OF PETROPHYSICAL ANALYSIS OF VERT-LE-GRAND FIELD

### 2.1 GEOLOGICAL SETTING

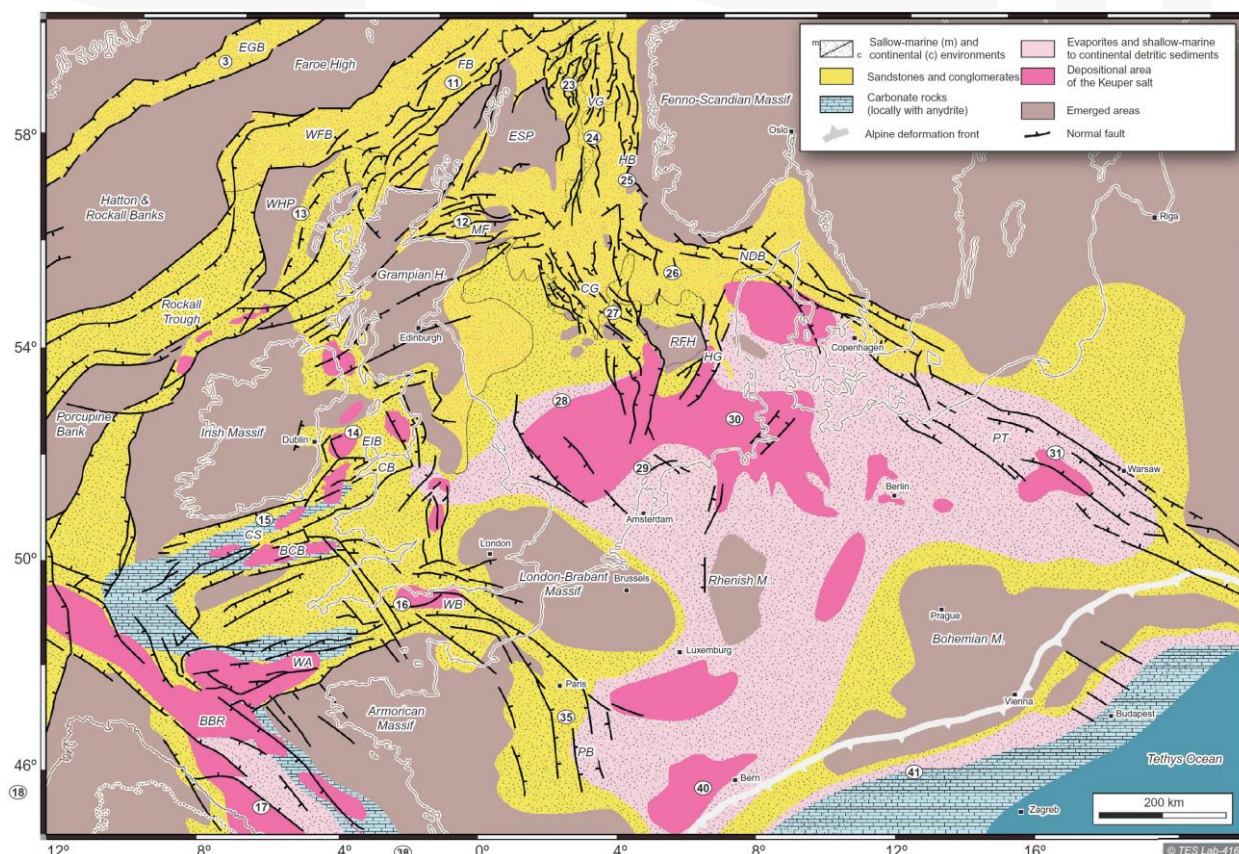
#### 2.1.1 Global tectonic and stratigraphic framework

In the Paris Basin and more generally in Western Europe, the Triassic sediments were formed under a hot and arid to semi-arid 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 paleogeographic situation at Triassic times (Figure 1A) shows that sedimentary formations were deposited in the intra-continental Paris Basin, which is surrounded by the Massif Central, the Armorican Massif and the London-Brabant Massif, both remnant highs of the Variscan orogeny. While the rifting processes became more active, the whole domain shows a general marine embayment during the Early Jurassic times (Blakey, 2016), resulting in the deepening of the basin as attested by the Liassic sedimentary record (clays, marls, ...).



**Figure 1: Paleogeographic maps of Europe at the Triassic (225 Ma) and Jurassic (200 Ma) (Blakey, 2016). The red star highlights our study area.**

The early steps of the continental rifting in Western Europe started with the development of extensional tectonic since Upper Triassic (Keuper), which is expressed at a wide scale with the appearance of the identical major trends of normal faulting directions later observed during the Jurassic (Soto et al., 2017 – Figure 2). The Paris Basin was located on a NW-SE corridor of normal faults, which were inherited from Variscan structures of the underlying structural domains composing the basement (Matte, 1986; Guillocheau et al., 2000). The stratigraphic record of the Triassic clastic formations in the Paris Basin indicates that these faults were playing a significant role in the partitioning of sedimentary domains (Bourquin et al., 2002).

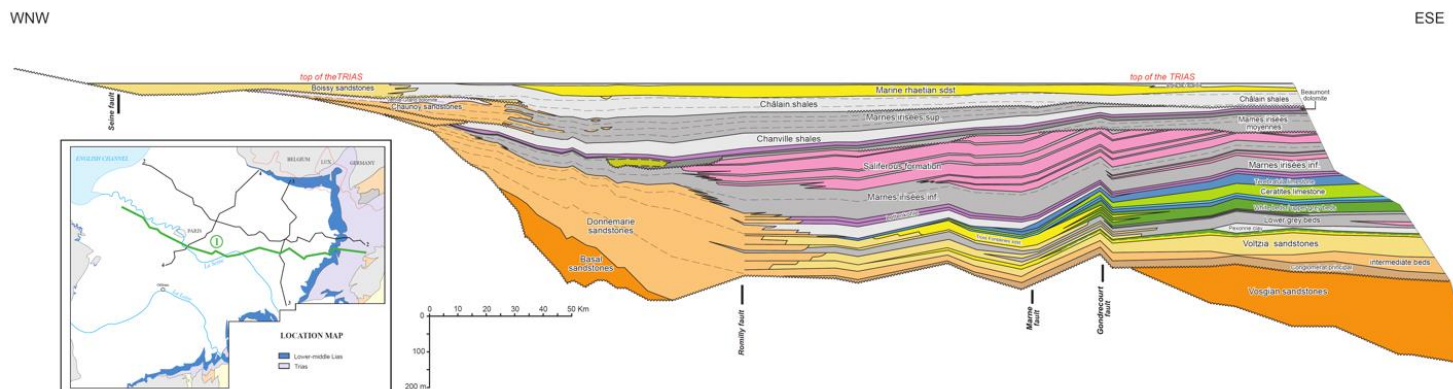


**Figure 2: Tectonosedimentary settings of Central and Western Europe during Carnian-Norian, ~238-206 Ma (Soto et al., 2017). The Triassic Paris Basin is located at the western edge of the area of sedimentation, with facies dominated by siliciclastic material.**

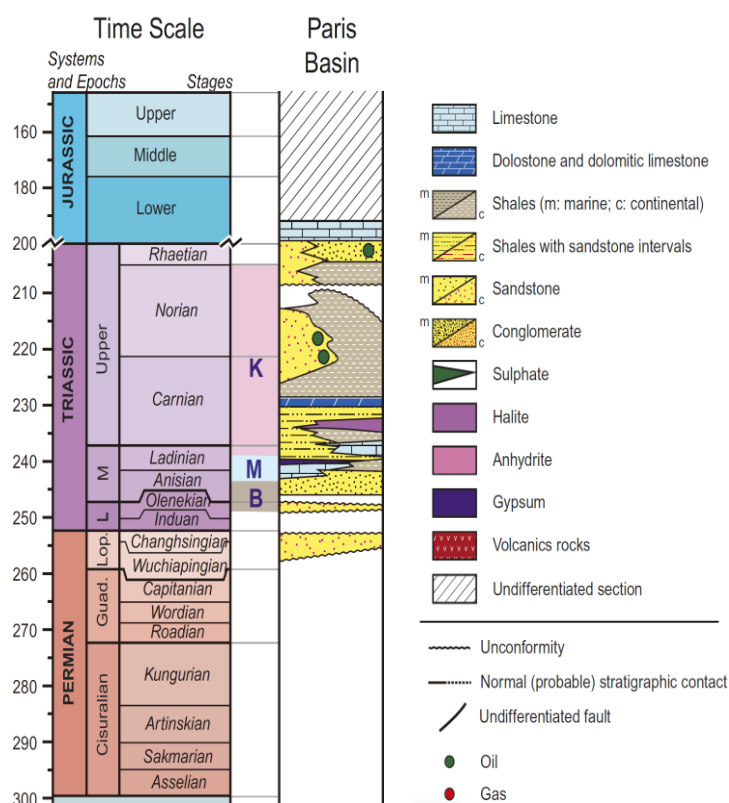
During Carnian-Norian period (238-206 Ma), the sedimentation along the western edge of the basin was dominated by coarse-grained siliciclastic material while the inner part of the basin was filled with shallow-marine to continental detrital sediments and evaporites, as shown in Figure 2. At a regional scale, these successions of siliciclastic formations are controlled by the variation of base level that defines major stratigraphic cycles (Bourquin and Guillocheau, 1996). The transgressive Carnian-Toarcian cycle is characterized by deposits of anastomosing braided rivers (“Grès à Roseaux”, middle Carnian), overlain by dolomitic and anhydrites coastal plain sediments (respectively “Dolomie de Beaumont” and “Marnes Irisées Supérieures anhydritiques”, middle Carnian to Norian), lateral equivalent to braided alluvial fans to the west (Chaunoy Formation). After a major intra-Norian unconformity, i.e. Eo-Cimmerian unconformity, the sedimentation is mainly composed of dolomitic coastal plain equivalent to fluvio lacustrine deposits to the west (“Grès de Boissy”), considered as Norian to Rhaetian. This lateral facies variation from west to east within the Paris Basin testifies of a strong connection between the continental aerial domain and the depocenter, showing the influence of a semi-arid climatic regime on the type of sedimentation. To the west of the basin, those formations are lying unconformably on the basement and thicken towards the east, where they interdigitate with the fine-grained sequences (Delmas et al., 2002 –Figure 3).



A significant tectonic tilt from SE to NW occurred during the Carnian-Liassic cycle associated with a migration of fault activity (Bourquin et al., 1997). It is expressed in the stratigraphic record by a truncation of “Marnes irisées supérieures” sometimes until lower Carnian salt deposits to the east. It also caused the appearance of marine sandstones in areas previously dominated by fine-grained continental deposits. Later, the open marine facies of lower Liassic conquered the whole basin as the subsidence stepped up.



**Figure 3: Chronostratigraphic chart of the Triassic formations found along a W-E profile across the Paris Basin (modified from Delmas et al., 2002). Chaunoy Formation are deposited on the western edge of the basin, in unconformity on the basement from the Armorican Massif. The Vert-le-Grand dolomites are situated on the top of Chaunoy sandstones.**



**Figure 4: Location of oil reservoirs in the Triassic siliciclastic formations (Soto et al., 2017, from Perrodon, 1990). The W-E facies variations represented in Fig. 2-3 are sketched for the Triassic period.**

The facies changes described above offer a privileged configuration for fluid migration and especially for trapping hydrocarbons in the different sandstone horizons onlapping the basement (Soto et al., 2017 – Figure 4). Structural traps may also occur against faults, which could act as fluid pathways. The reservoir rocks are the Donnemarie sandstones (i.e. equivalent to lower Carnian salt series), the Chaunoy sandstones with their associated Vert-le-Grand dolomites, and the Rhaetian sandstones (Figure 4). The source rock for these reservoirs is suspected to be the Toarcian “Schistes carton” that may have been put in contact with the Keuper rocks locally against faults or which fluids may have transferred per descensum along faults.

### **2.1.2 Local stratigraphic and structural framework**

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), which caused the accumulation of thick alluvial sandstones on top of the basement (Figure 5).

The Chaunoy Formation 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 pedogenic 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 preserved in more lacustrine; they grade eastward towards the marine Rhaetian sandstones (Novikoff et al., 2017) precursor of the Liassic transgression. In the Paris Basin, across this sequence, and more specifically from Chaunoy Sandstones to Vert-le-Grand Dolomite, several well sites are studied since these formations are already oil reservoirs and bear a huge volume of trapped water (as much as 99%).

In terms of local structural settings, the area located SW of the regional-scale Bray fault is perturbed by several accidents, such as the NNW-SSE Etampes-Rambouillet fault or the NE-SW Melun fault. Some regional seismic lines indicate the presence of local tectonic disturbances that may have a great impact at the scale of an exploitation field (lines EW3 and NS1b in Beccaletto et al., 2011 – Figure 6). In our case, some small-scale faults were identified in industrial reports based on seismic interpretations. These faults seem to bind the reservoir reached by industrial boreholes to the west and south (Figure 5).

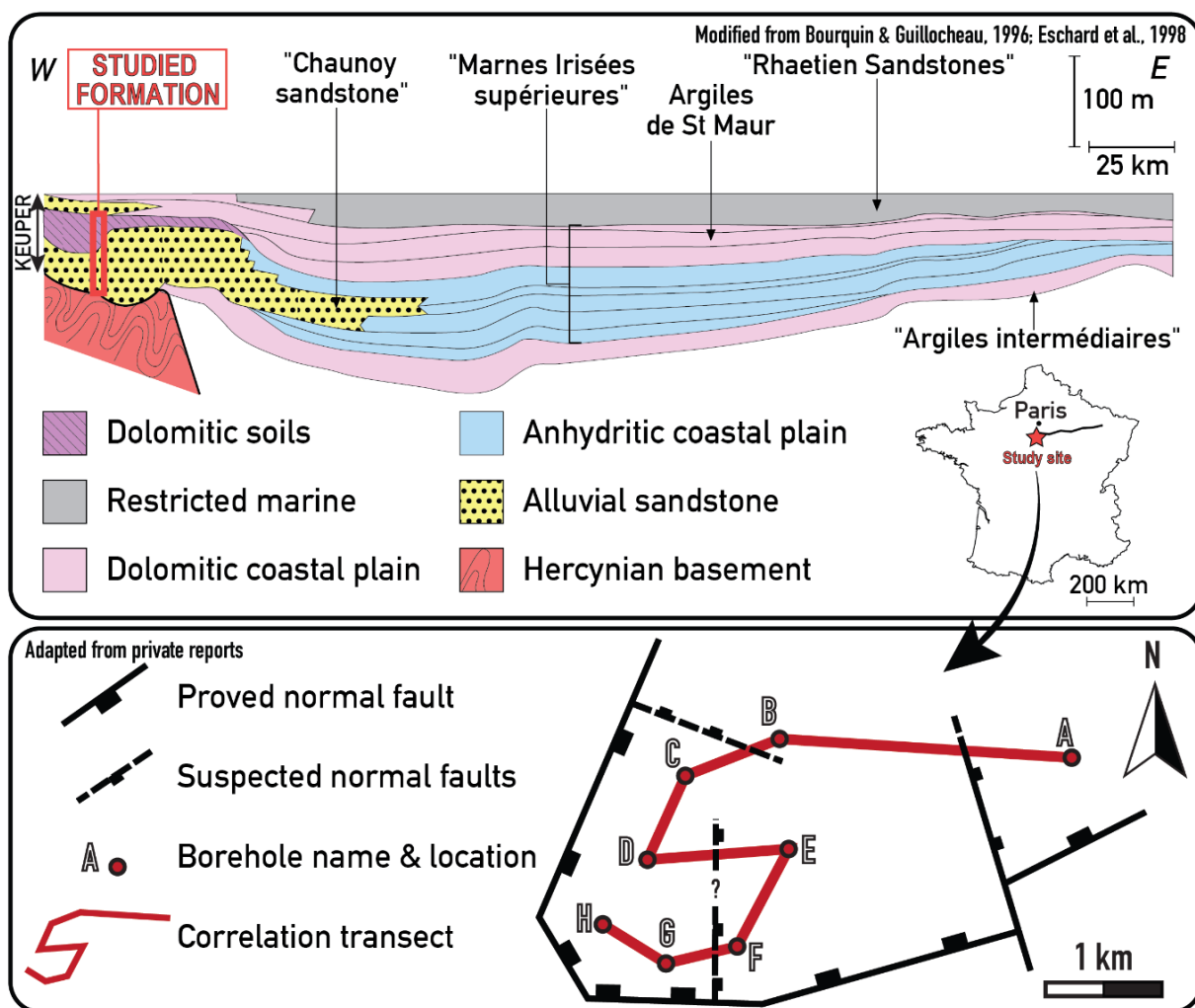
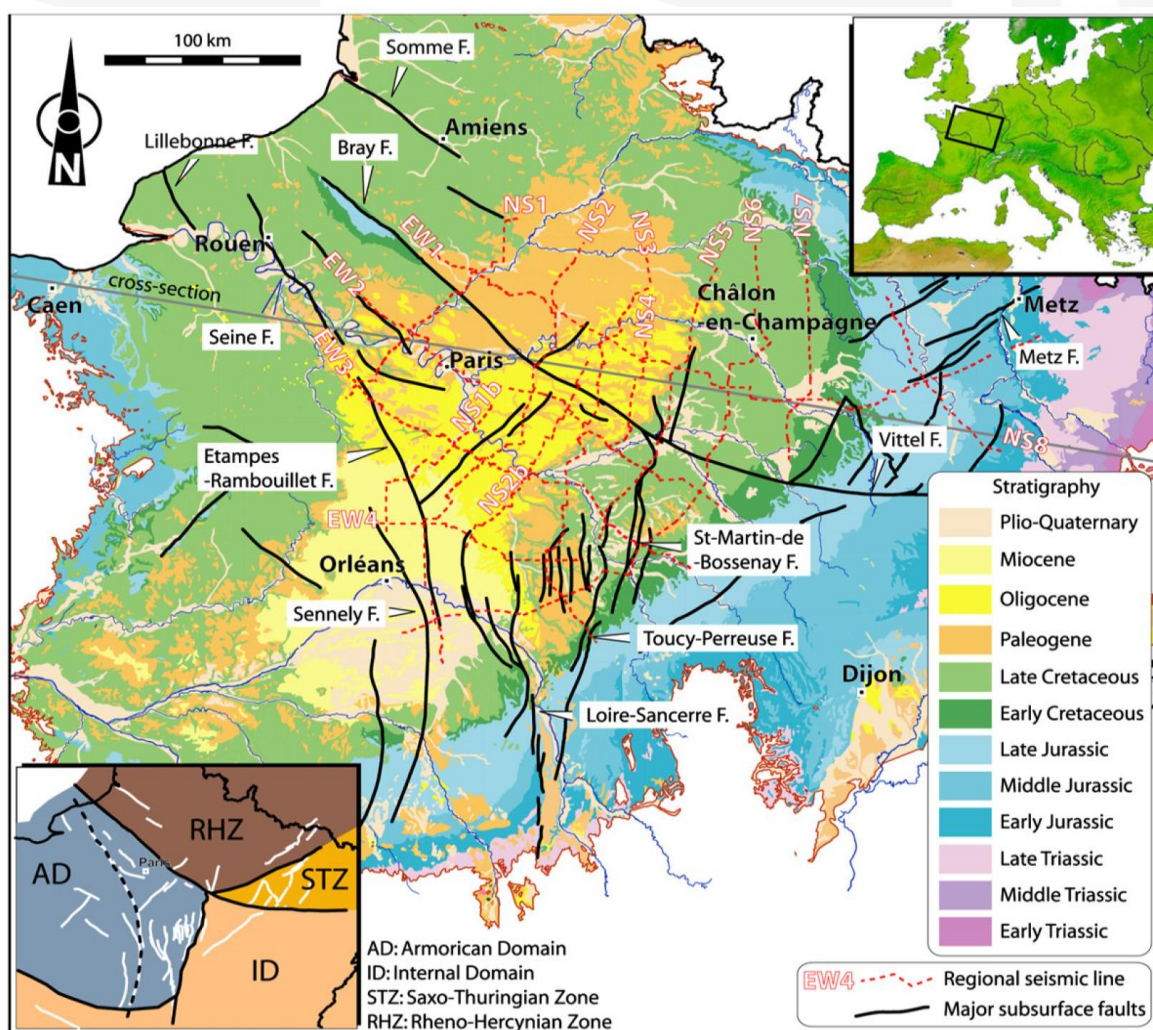


Figure 5 (previous page): Local stratigraphic and structural context. The study area is located to the west of the stratigraphic profile that shows the truncation of “Marnes Irisées Supérieures” to the east and facies variations with Chaunoy sandstones to the west (modified from Bourquin and Guillocheau, 1996). The location of industrial boreholes A to H studied in the frame of this deliverable is indicated, as well as the local correlation transect that is presented in the part 2.4. The faults that bound the study area are adapted from industrial reports since their precise location can only be deduced from seismic lines.



**Figure 6: Structural scheme and location of regional seismic lines (Beccaletto et al., 2011). In particular, the seismic interpretations of lines EW3 and NS1b display some local disturbances around the study area.**



## 2.2 LITHOFACIES, FACIES ASSOCIATION & DEPOSITIONAL ENVIRONMENT

### 2.2.1 Methodology

A thorough sedimentological description of 470 m of linear rock core was conducted together with the collection of 159 plugs for performing petrophysical and petrographic analyses (part 2.3.). During this work, the main lithological units as well as the lithofacies types were defined. The lithofacies definition follows the classification of Miall (1978) and Bourquin et al. (1998), including i) a capital letter defining the lithology:

- S: “Sand” for sandstones
- G: “Gravel” for conglomerates
- F: “Fine” for silts and clays
- D: “Dolomite”,

And ii) one or several lowercase letter(s) precisising the structure:

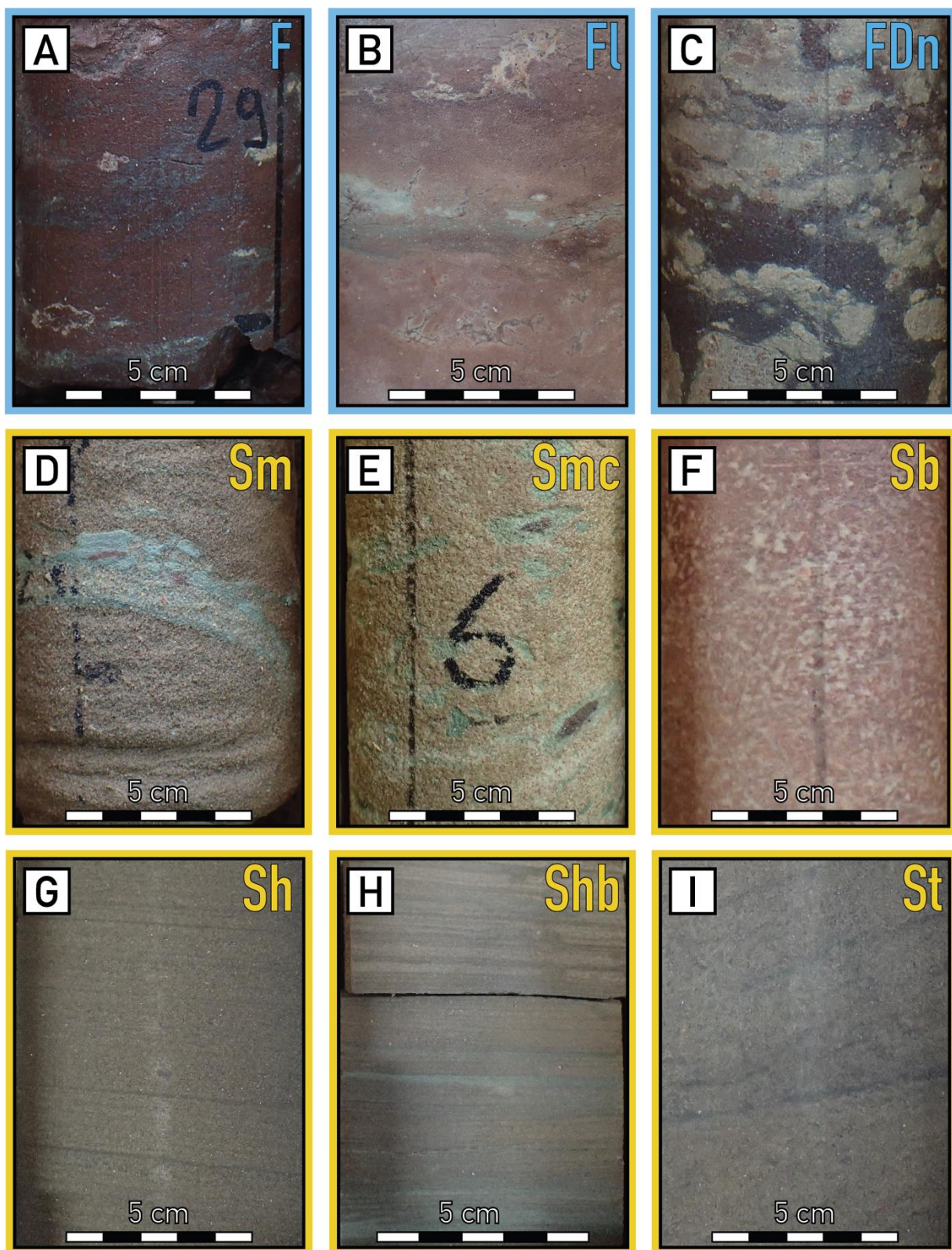
- t: “through-cross bedded”
- p: “planar-cross bedded”
- h: “horizontal lamina”
- b: “bioturbation”
- m: “massive”
- mu: “massive matrix-supported”
- mc: “massive clast-supported”
- n: “nodule”

Note that some heterolithic facies were also defined, they gather several lithologies (Gi, FI, FDn). Then, following the methodology of Bourquin et al. (1998), we i) deduce the depositional processes based on lithofacies description and ii) interpret the sedimentary environments by combining the inferred processes and the facies association.

### 2.2.2 Lithofacies definition

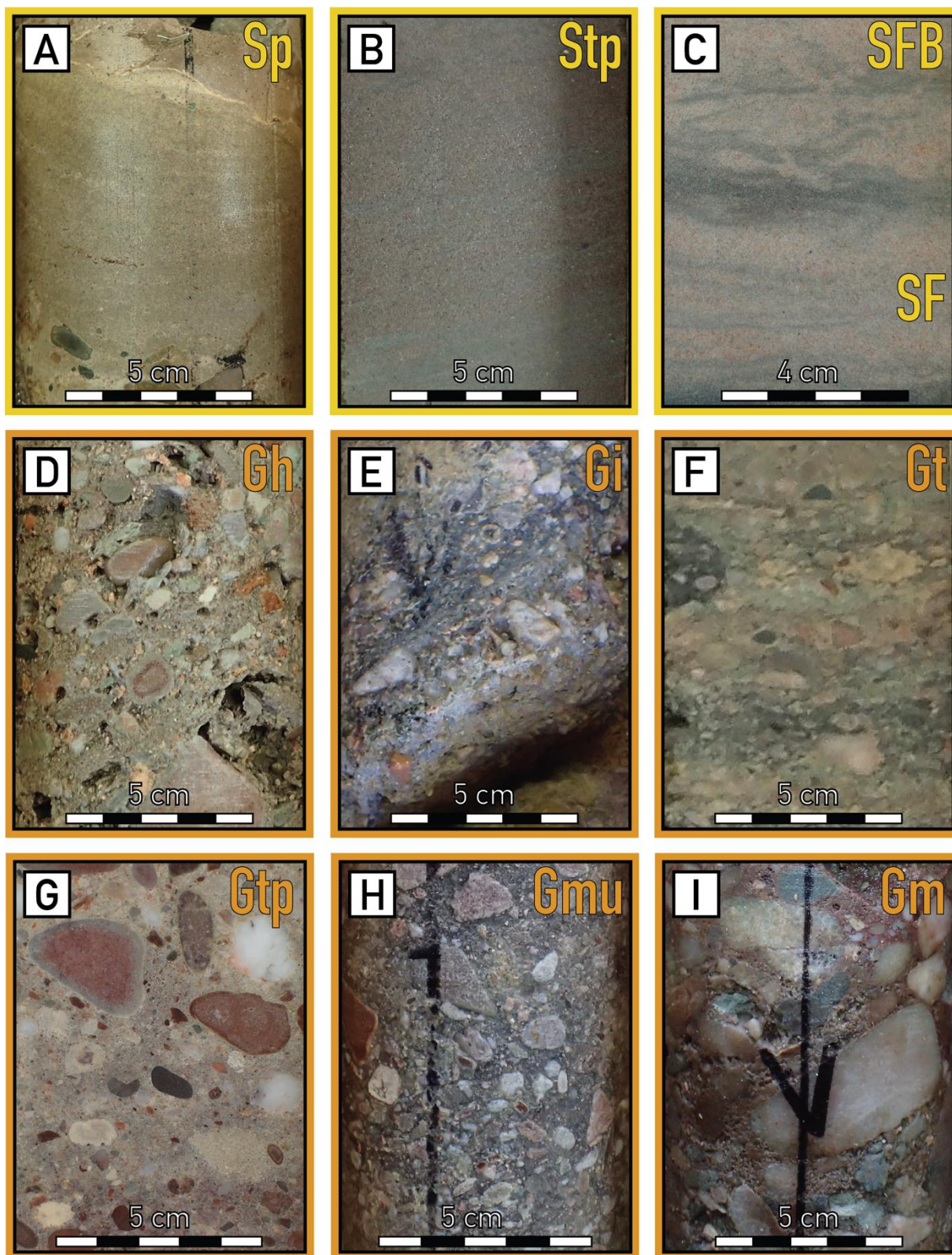
The macroscopic descriptions of cores highlight the occurrences of continental detrital facies alternating with massive dolomites (Figure 7, Figure 8 and Figure 9). A total of 23 main facies was defined (Table 1) including 3 clay & silt facies (Figure 7A-C), 10 sandstone facies (Figure 7D-I & Figure 8A-C), 6 conglomerate facies (Figure 8 D-I) and 4 dolomite facies (Figure 9A-I). According to previous works (Simons et al., 1965; Bourquin et al., 1998), the integration of facies and sedimentary structures can deliver insights in terms of hydrodynamic regimes.





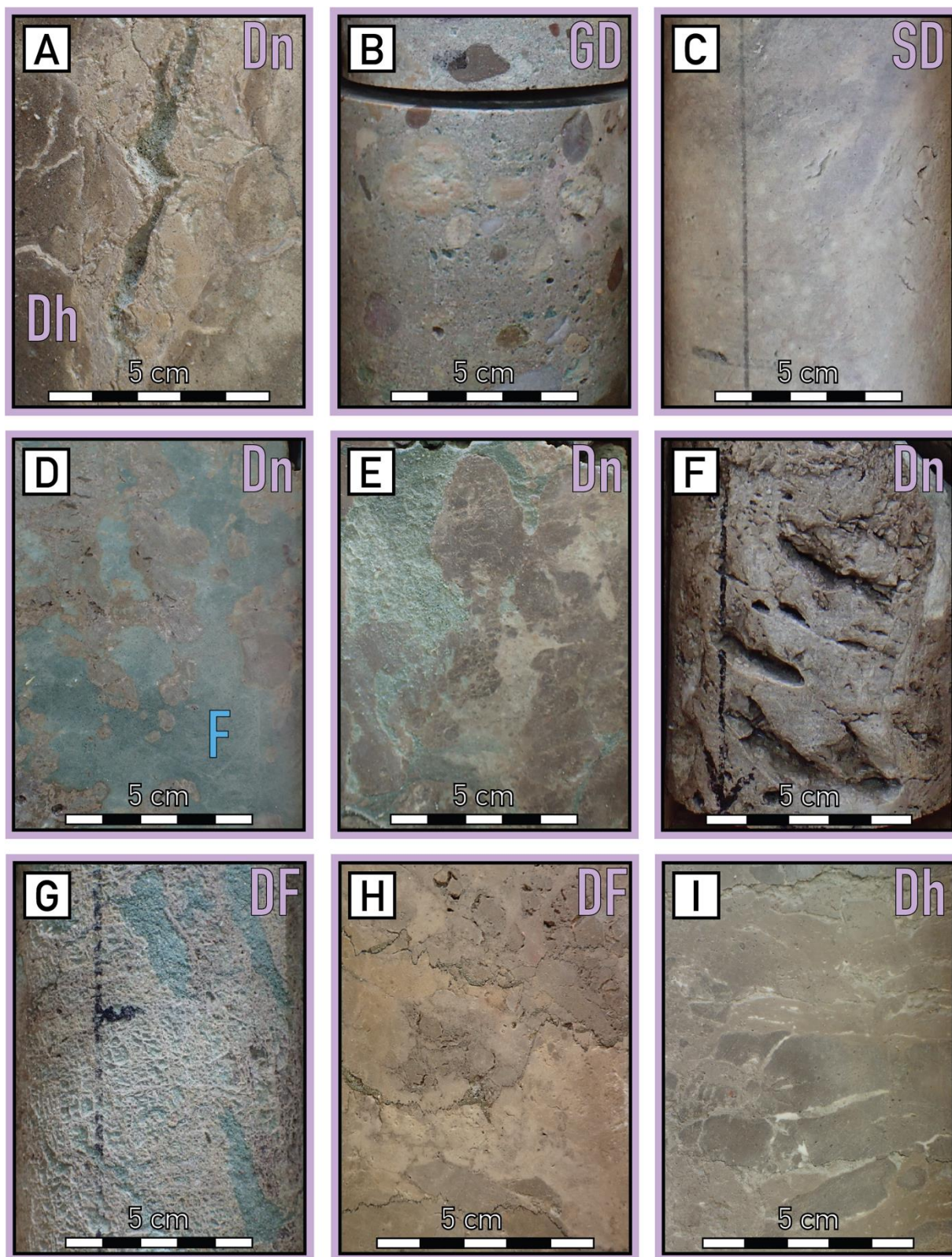
**Figure 7: Clays, silts and sandstones facies types. (See Table 1 for description).**





**Figure 8: Sandstones and conglomerate facies types. (See Table 1 for description).**





**Figure 9: Dolomite facies types. (See Table 1 for description).**

**Table 1: Lithofacies table. Facies code are adapted from Miall (1978) and Bourquin et al. (1998).**

Facies code		Sedimentary structures	Depositional & diagenetic processes
CLAYS & SILTS	F	Clays or silts	Deposition from suspension
	FI	Clays or silts with interbedded centimeter to millimeter thick planar laminated sand	Overbank or waning flood
	FDn	Poorly-developed nodular dolomite floating within a clayed and/or silty matrix	Deposition from suspension, overprinted by pedogenic dolomitization
SANDSTONES	Sm	Massive fine-grained sandstones to conglomerates with clast-supported, ungraded, well- to poorly-sorted, sometimes base and top bioturbated	Subaerial hyperconcentrated flows, Subaqueous high-density turbidity currents
	Smc	Massive coarse-grained sandstones to conglomerates, well- to poorly-sorted, pebbles and clasts, erosive basal boundary	Lag deposits or hyperconcentrated flows
	Sb	Same as above, bioturbated	Same as above, within water level
	Sh	Fine- to coarse-grained sandstones, moderately to well-sorted, planar or subplanar lamination highlighted by granulometry variations or soft pebbles	Planar bed flow (upper flow regime)
	Shb	Same as above, bioturbated	Subaqueous planar bed flow
	St	Medium- to very coarse-grained sandstones, poorly sorted, trough cross-bedded highlighted by mm to cm clasts or soft pebbles	Megaripples 3-D, upper part of the lower flow-regime
	Sp	Medium- to very coarse-grained sandstones, poorly-sorted, planar cross-bedded	Megaripples 2-D, medium part of the lower flow-regime
	Stp	Medium- to coarse-grained sandstones, poorly-sorted, planar or trough cross-bedded highlighted by mm to cm clasts or soft pebbles	Megaripples 3-D and 2-D, upper and medium part of the lower flow-regime
	SF	Clay-rich sandstones	Overbank
	SFb	Same as above, bioturbated	Overbank within water level
CONGLOMERATES	Gh	Conglomerate, very poorly sorted, planar bedded highlighted by granulometry variations	Planar bed flow (upper flow regime)
	Gi	Conglomerate, poorly-sorted planar bedded highlighted by clays and silts	Alternation between planar bed flow (upper flow regime) and deposition from suspension
	Gt	Conglomerate, matrix-supported, very poorly-sorted, erosive basal boundary	3-D megaripples, upper part of the lower flow-regime
	Gtp	Conglomerate, matrix-supported, very poorly-sorted, erosive basal boundary	3-D and 2-D megaripples, upper and medium part of the lower flow-regime
	Gmu	Conglomerate, matrix-supported (silt and coarse-grained sandstone), very poorly sorted, sometimes erosive basal boundary	Subaerial or subaqueous plastic debris flows
	Gm	Clast-supported conglomerate, poorly sorted, erosive basal boundary	Lag deposits, high hydrodynamic conditions
DOLOMITES	Dn	Well-developed nodular and vertical dolomite within conglomerates, sandstones and fine facies	Pedogenic dolomitization associated with water table fluctuations and affecting various facies
	Dh	Homogeneous massive dolomite, sometimes cracks filled by clays, silts or sandstones, some stylolites	Dolocrete development
	DF	Massive dolomite with vugs, greenish clays and/or silts numerous stylolites	Dolocrete or pedogenic dolomite affected by karstification
	GD/SD	Dolomitized very fine sandstone to conglomerate, possible stylolites	Dolomitization of a detrital deposit

The clay & silt facies (Table 1) are composed of:

- Massive red, brown to dark clays (F, Figure 7A) that may locally exhibit bioturbation-like features (Figure 7B). They are the result of suspension depositional processes.
- Planar laminated siltstone and sandstone may be interbedded within clays (Fl, Figure 7B), probably characterizing the lower part of the upper-flow regime and corresponding to overbank or waning flood depositional processes,
- And floating poorly developed nodular-dolomite within red clays (FDn, Figure 7C), clearly suggesting pedogenic processes.

Sandstone facies were also identified and interpreted in terms of depositional processes (Table 1):

- Firstly, we identified lithofacies Sm that may be intercalated between sandstones, dolomites and clays (Figure 7D). It coincides to well-sorted decimeter- to meter-thick layers, showing locally bioturbation traces at its top and base. This facies is promptly deposited under the action of subaerial hyperconcentrated flows and/or subaqueous high-density turbidity currents (Ghibaudo, 1992; Bourquin et al., 1998). We also rarely observed lithofacies Smc (Figure 7E) showing an erosive basal boundary, interpreted as deposited under the action of hyperconcentrated flows, probably corresponding to lag deposits.
- We may locally identify strongly bioturbated sandstones (Sb, Figure 7F) displaying decimeter- to pluri-meter-thick beds, intercalated between sandstones, dolomite and clays. The high density of bioturbation indicates a subaqueous deposition.
- Planar cross-bedded sandstones were also identified, they exhibit planar to subplanar laminations (Sh, Figure 7G), forming centimeter- to decimeter-thick beds that may alternate with centimeter-thick clay levels. Locally, these sandstones may correspond to pluri-meter-thick beds displaying bioturbation evidences (Shb, Figure 7H). Sh and Shb beds do not exhibit any erosional base, they further show a gradational transition with the underlying rocks. Sh characterizes a planar lower or upper flow regime.
- Trough-cross-bedded poorly sorted sandstones to conglomerates were characterized (St, Figure 7G), they may display fining-upward pluri-meter-thick beds together with decimeter-thick beds. We also characterized decimeter- to pluri-meter-thick beds of Sp (Figure 8A) and Stp (Figure 8B), corresponding respectively to trough cross-bedding and planar cross-bedding sandstones. They are interpreted as 3-D and 2-D megaripple migration.
- Finally, we characterized lithofacies SFb and SF (Figure 8C), organized in decimeter- to meter-thick beds. These facies present features similar to Fl with a higher sand content, they are thus interpreted as deposited under the action of the lower part of the upper-flow regime, corresponding to overbank or waning flood depositional processes.



Core description allows us to determine six conglomerate facies highlighting several depositional processes (Table 1):

- Planar bedded conglomerates (Gh, Figure 8D), showing erosive base and containing dolomite pebbles, overlying thus dolomites. They may highlight a fining upward evolution and are deposited under the action of planar bed flows.
- Lithofacies Gi is underlined by the alternation between clays and poorly sorted and planar bedded conglomerates (Figure 8E). It is deposited under the action of planar bed flow alternating with suspension. Note that this facies may present a partial dolomitization at its base.
- Very poorly sorted Gt (Figure 8F) and Gtp (Figure 8G), displaying trough and/or planar cross-bedded, are also observed. They are deposited under the action of 3-D and 2-D megaripple migration.
- Lithofacies Gmu (Figure 8H) corresponds to a matrix-supported conglomerate, it may show partial dolomitization at its base and displays sometimes an erosive base. Depositional processes of Gmu correspond to subaerial or subaqueouslastic debris flow.
- Finally, lithofacies Gm (Figure 8I) was also recognized. Given its erosive basal boundary and pluri-centimeter-scale gravel content, it is interpreted as deposited under high hydrodynamic conditions (lag deposit).

The studied cores display also numerous levels of dolomites showing diverse macrostructures (Table 1):

- As already evoked, sandstones and conglomerates may present evidences of dolomitization. Depending on the intensity of dolomite cementation/replacement, the primary sedimentary structures may partially to fully be erased, conducting to homogeneous dolomitized conglomerates (GD, Figure 9B) and sandstones (SD, Figure 9C).
- The first dolomite lithofacies corresponds to nodular dolomite (Dn, Figure 9A). It may be associated with other dolomite facies and overlies sandstones deposits. Dn is associated with root traces and clays (Figure 9A, D). It displays more or less coalescent nodules, up to massive nodular dolomites that may show centimeter-thick vugs (Figure 9D, E).
- Massive homogeneous dolomite is also present (Dh, Figure 9A, I). It may include cracks filled by clays, silts or sandstones, and presents a few stylolites. This facies shows an irregular and gradual basal boundary. According to earlier works, this facies is interpreted as a dolocrete development (phreatic environment diagenesis, Spötl & Wright, 1992).
- Finally, we also characterized massive dolomites containing clay-filled vugs and numerous stylolites (DF, Figure 9G, H). We interpreted these lithofacies as either dolocrete or pedogenic dolomite that may be affected by karstification.

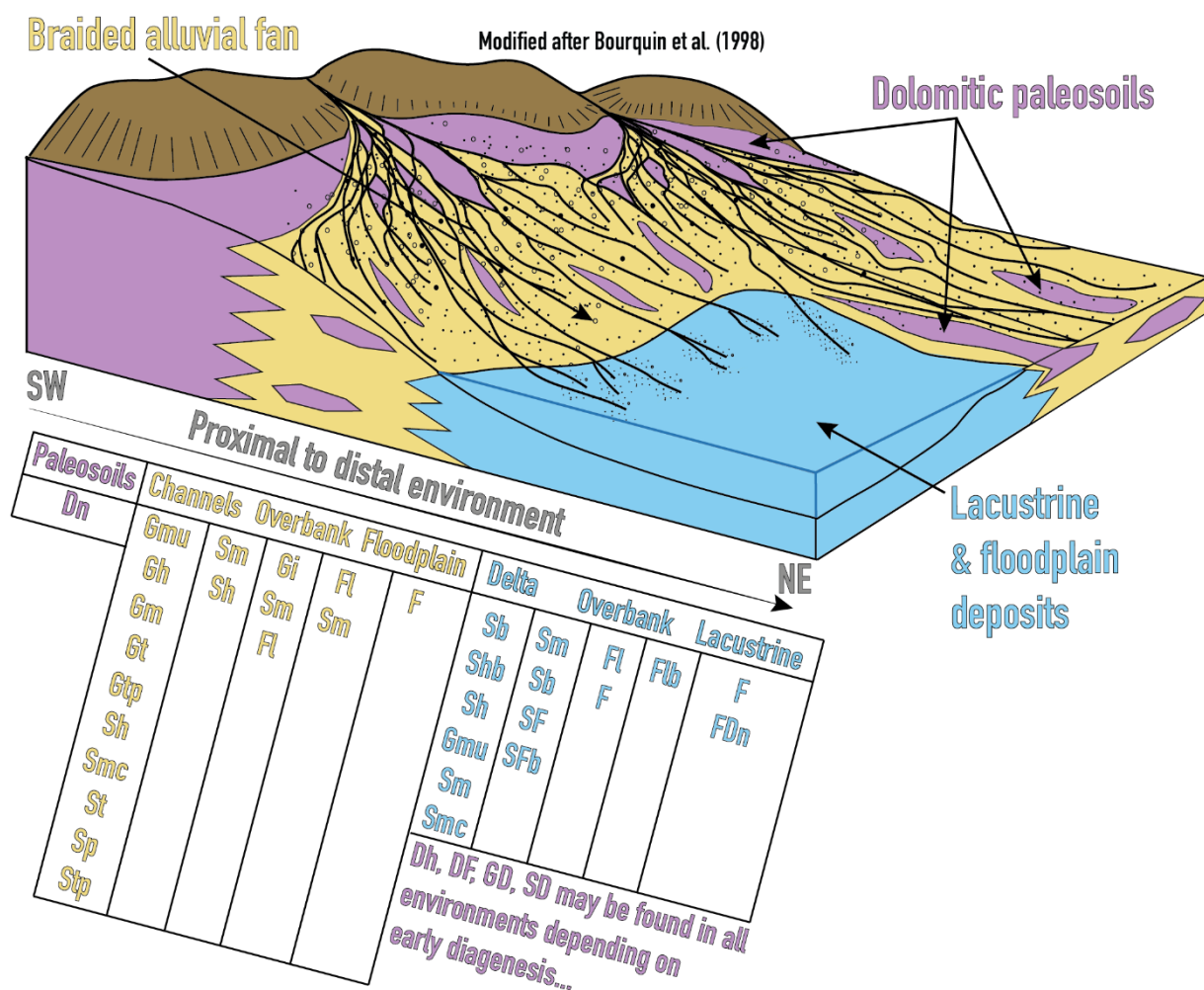
### 2.2.3 Facies association & depositional environments

The studied deposits correspond to the extreme western part of the Chaunoy Formation accumulated in the Paris Basin during Triassic times (Figure 3). As already stated by Bourquin et al. (1998), it corresponds to alluvial fan deposits widely affected by dolomite development. According to vertical stacking of facies (*i.e.* genetic sequences) and previous interpretation of depositional processes, we can define facies associations corresponding to distinct depositional environments (Figure 10):

- Dolomite paleosoils overly previous accumulation of detrital sediments and may be associated with other dolomite facies (Dh, DF, GD, SD) forming pluri-meter- to decameter-thick beds. They relate to periods of non-deposits and may represent paleogeographical high points.
- Braided alluvial fan deposits correspond to the most proximal area. It gathers three facies associations corresponding to three main environments organized from proximal to distal areas:
  - Channels and debris flow deposits, including plethora of conglomerates (Gh, Gm, Gt, Gtp, Gmu) and sandstones (St, Stp, Sm, Smc, Sh, Sp) facies mostly showing pluri-meter-thick beds, characterized by bedload deposits, 2-D/3-D migration of megaripples, subaerial debris flow and hyperconcentrated flows. They are often overlying by dolomite facies that may show evidences of paleosoils (Dn, Dh). Furthermore, they may contain dolomite pebbles outlining the erosion of previously developed dolomite paleosoils.
  - Overbank deposits, including centimeter- to meter-thick beds of conglomerates (Gi) and sandstones (Sm, Sh) interbedded in heterolytic clay intervals (Fl, F) Such deposits result from quieter periods of flow allowing decantation, interrupted by small episodes of higher flow regime.
  - Floodplain deposits (Fl, F) corresponding to the quieter environment within the braided alluvial fan environment.
- Lacustrine deposits characterized by a quieter flow, subdivided in three main environments:
  - Subaqueous fan delta channels partially bioturbated, mainly composed of subaqueous planar concentrated flow (Sb), planar bed flow (Sh), high-density turbidity currents (Sm) and local hyperconcentrated flow (Gmu, Smc). These deposits are thinly bedded and correspond to the distal part of alluvial fan, accumulated in lacustrine environments as attested by the occurrence of bioturbation.
  - Subaqueous overbanks are rarely observed. They mainly correspond to bioturbated (Sb) and clay-rich sandstones (SF) interbedded in heterolytic clay intervals that may be also bioturbated (F, Fl, Flb). Like above, they mainly correspond to decantation episodes punctually interrupted by higher flow regime.
  - Lacustrine deposits are also rare, they correspond to the more distal environment, highlighting only clay-silt deposits (F) that may present poorly developed nodular dolomite

(FDn). Such facies attest of drier periods associated with emersion, corresponding to unrecorded sedimentary periods.

- Finally, dolocrete successions are widely observed (Dh, DF, GD, SD). They correspond to a phreatic dolomitization of detrital deposits and may affect the whole recognized sedimentary lithofacies. Consequently, we cannot associate these facies with a peculiar environment and rather have to refer to the underlying and overlying deposits for understanding the depositional environment evolution. Nevertheless, such dolocrete development is resulting from an overlying emersion event potentially characterized by a paleosol development that may be either preserved or eroded.



**Figure 10: Depositional environments and facies association definition for our study, based on and modified after Bourquin et al. (1998).**



## 2.3 MICROTEXTURES, DIAGENESIS & PETROPHYSICAL PROPERTIES

### 2.3.1 Methodology

#### 2.3.1.1 Thin-sections petrography

A total of 212 thin sections (53 at the GEC and 159 at Vermilion) were thoroughly analyzed for textural and diagenetic purposes (texture, fabric, grain types, pore types, mineralogy, cementation or dissolution features...). Each thin section was impregnated with blue-dyed epoxy to identify the pore space and only a few of them has been stained with alizarine red-S to differentiate carbonate minerals (calcite is stained while dolomite remains unstained; Dickson, 1966).

Petrographic observations were accomplished using a conventional polarized microscope (PPL: plane-polarized light, XPL: cross-polarized light, RL: reflected light). The dolomite texture has been described using the classification of Randazzo & Zachos (1983), while porosity has been described using the classification of Choquette & Pray (1970) and Lønøy (2006). We also used cathodoluminescence microscopy (CL) for characterizing 32 thin-sections. This technique is based on the luminescence property of minerals bombarded with an electron beam. Luminescence occurs in impure crystals containing small amount of ions acting as activators (mainly  $Mn^{2+}$ ) or inhibitors (mainly  $Fe^{2+}$  and  $Fe^{3+}$ ). Indeed, the impurities and defects of minerals linked to their growth conditions are the main controlling factors of luminescence (Walker, 1985). Note that other ions may act as activators ( $Pb^{2+}$ , Rare Earth Elements) or inhibitors ( $Ni^{2+}$ ,  $Co^{2+}$ ). Cathodoluminescence microscopy is performed for better characterizing the growth features and genetic/temporal relationships between the crystals (Machel & Burton, 1991). According to Mason (1987), the color and intensity of carbonate minerals is mainly linked to the  $Mn^{2+}/Fe^{2+}$  ratio and the concentration of these two elements. To conclude, CL aims to discriminate differences in luminescence that may highlight variations of the fluids at the origin of mineral precipitation.

#### 2.3.1.2 Petrophysical measurements

A total of 159 plugs of one inch in diameter were analysed for their petrophysical properties at the GEC laboratory, additionally to the already existing dataset of Vermilion (712 plugs of one inch diameter). The porosity and density of the 712 plugs of Vermilion and 46 plugs at the GEC were measured with the triple-weight method by assessing the plug mass under three different conditions: fluid-saturated, suspended in the saturating fluid and dried. Due to sample cohesion (few partial disintegrations of plugs caused by water imbibition), helium pycnometry measurements, from which porosity was calculated, were done on 117 plugs at the GEC laboratory. Furthermore, gas permeability measurements were performed with a Hassler cell using nitrogen. During the measurements, the flow was laminar. Permeability measurements were performed with a steady state permeameter (lower limit of  $10^{-1}$  mD) at a confining pressure of 27 bars for the GEC measurements (confining pressure unknown for the Vermilion dataset).

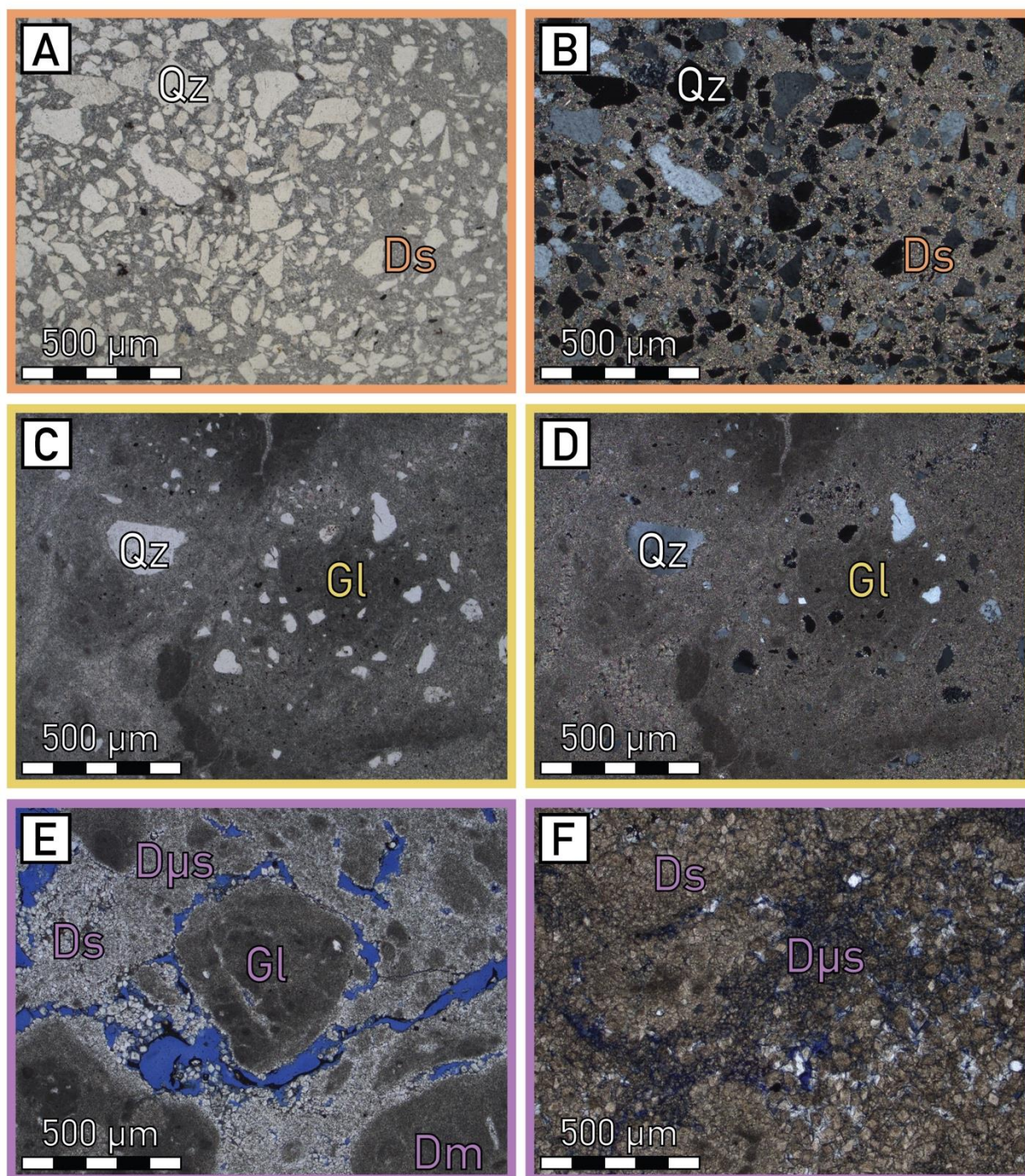
### 2.3.2 Microtextures

Based on petrographic observations, we simplified the classification using the definition of 6 main microtextures (Table 2). For dolomite samples, we described 3 microtextures (Figure 11): i) Quartz-rich crystalline dolomite; ii) Glaebular and quartzic crystalline dolomite, iii) Glaebular & crystalline dolomite. For siliciclastic samples, we also defined 3 main microtextures (Figure 12): iv) Polygenic conglomerate; v) Clay-rich sandstone; vi) Clean sandstone. Their main recognition criteria are summarized in the Table 2 together with a succinct description of their porous network (Figure 13).

**Table 2: Main recognition criteria of the microtextures described in this work.**

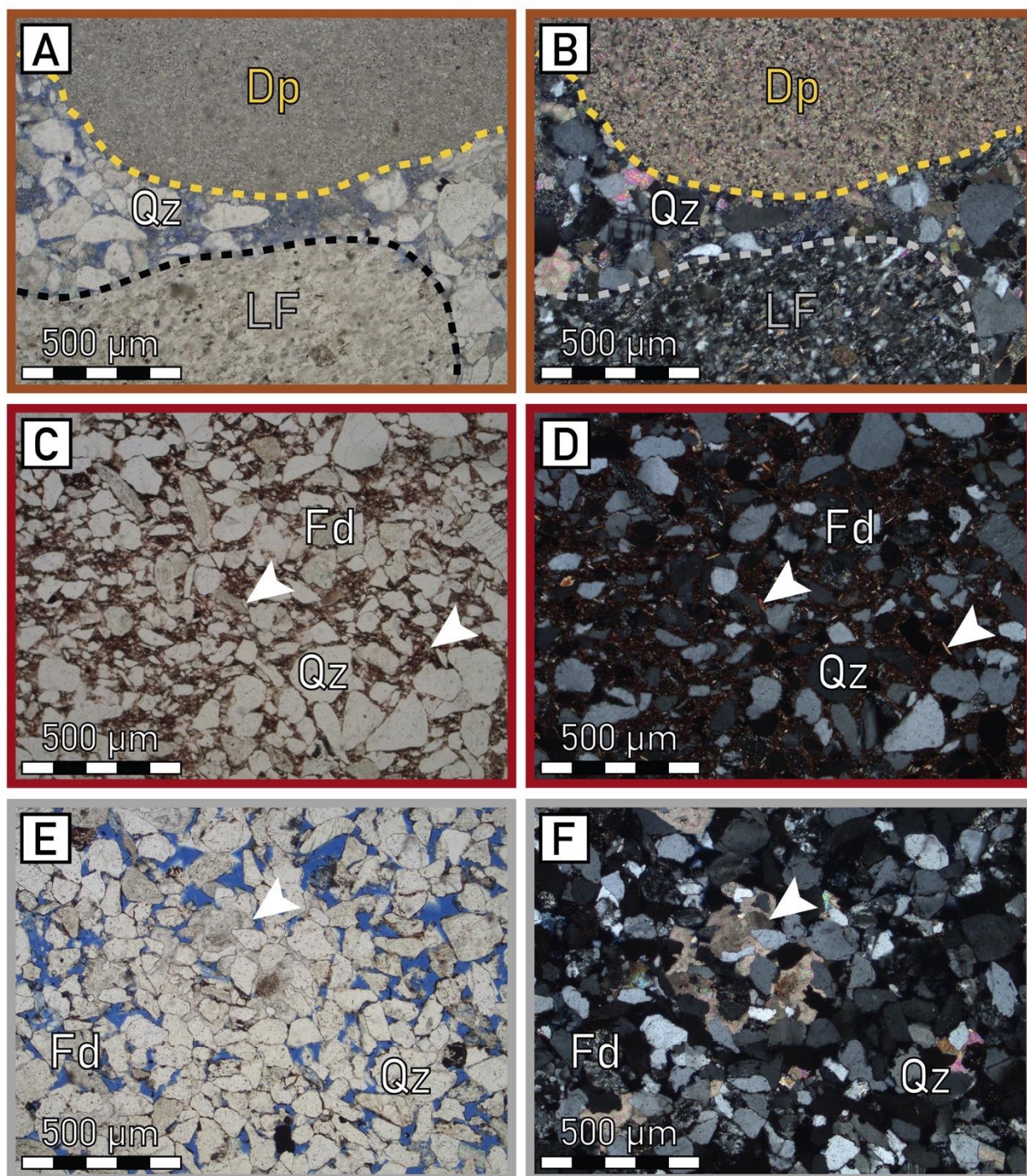
Microtexture	Components	Matrix	Porous network	Related Figs
<b>Quartz-rich crystalline dolomite</b>	Mainly inframilimetric subangular to subrounded quartz	Dolosparite groundmass (mainly equigranular and sutured mosaic)	Tight, vuggy and intercrystalline patches of porosity	11A,B 13D-F
<b>Glaebular and quartzic crystalline dolomite</b>	Mainly inframilimetric glaebules and floating (sub)rounded quartz	Dolosparite groundmass (mainly inequigranular and fogged mosaic)	Tight, patchy intercrystalline & vuggy porosity	11C,D 13D-F
<b>Glaebular &amp; crystalline dolomite</b>	Floating and touching inframilimetric to milimetric glaebules	Dolosparite groundmass (mainly inequigranular and fogged mosaic)	Tight, patchy intercrystalline & vuggy porosity	11E,F 13D-F
<b>Polygenic conglomerate</b>	Pebbles of dolomite, quartz and rock fragments, poorly sorted	Inframilimetric subrounded to subangular quartz, carbonate cement	Tight if cemented or intergranular porosity, molds	12A,B
<b>Clay-rich sandstone</b>	Inframilimetric subrounded to angular quartz, feldspar and muscovite, poorly sorted	Red clays matrix, sometimes illite clay coating	Microporosity of clays, possible molds (dissolved feldspars)	12C,D 13B-C
<b>Clean sandstone</b>	Inframilimetric rounded to subangular quartz, feldspar, moderately sorted	Sometimes dolosparite cement	Uniform intergranular porosity, sometimes tight if cemented	12E,F 13A-C





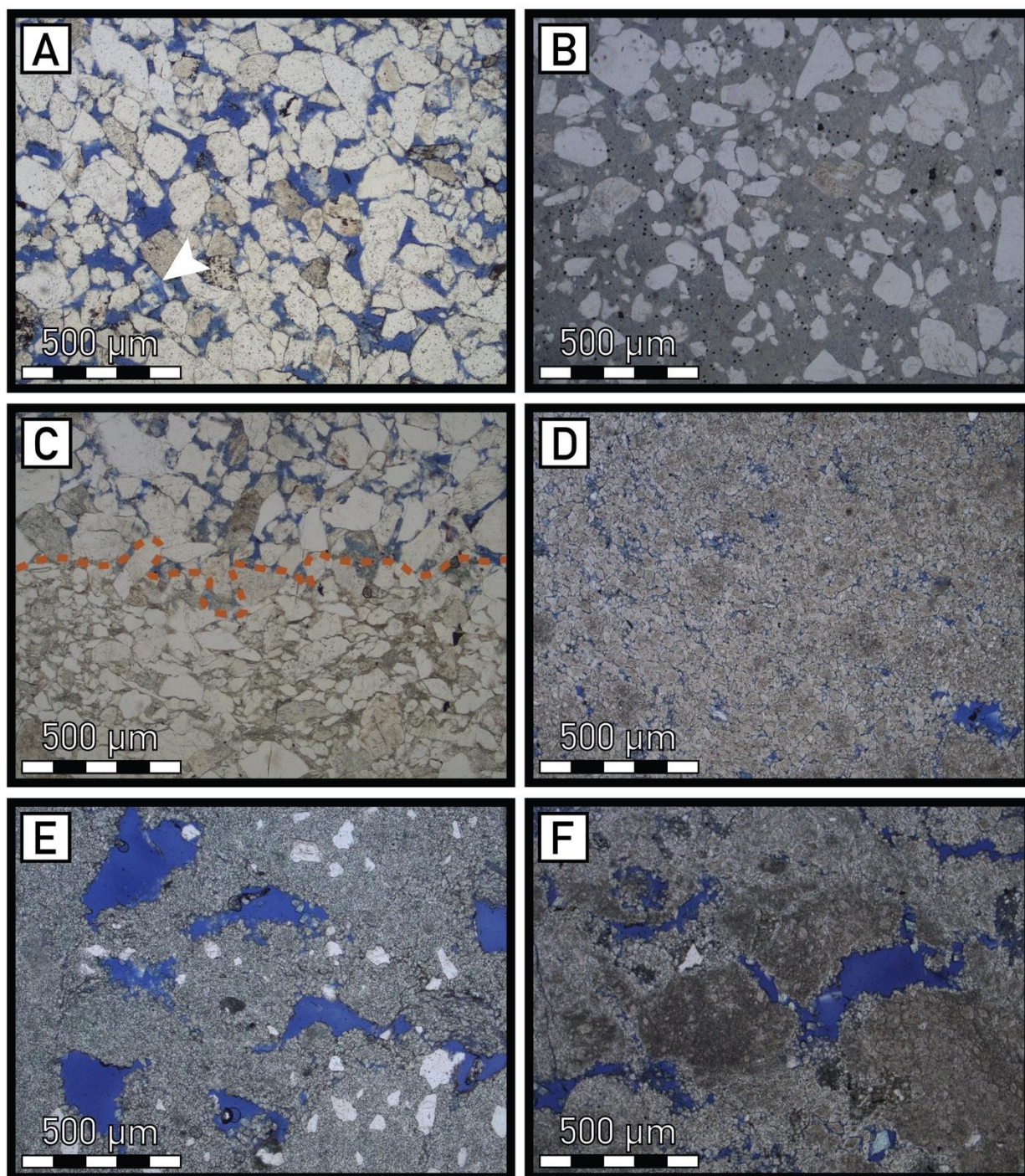
**Figure 11: Photomicrographs of dolomite samples. (A) PPL & (B) XPL views of a Quartz-rich crystalline dolomite with subangular to angular quartz (Qz) floating in a dolosparite matrix (Ds). (C) PPL & (D) XPL views of a glaebular & quartz-rich crystalline dolomite with subangular to subrounded quartz (Qz) floating in a dolosparite matrix associated glaebules (Gl). (E) & (F) PPL views a glaebular & crystalline dolomite rich in micrite glaebules (Gl), the matrix is composed of dolomicrosparite (Dμs) and dolosparite (Ds).**





**Figure 12: Photomicrographs of detrital samples. (A) PPL & (B) XPL views of a polygenic conglomerate containing dolomite pebbles (Dp) and lithic fragment (LF) embedded in a quartz-rich (Qz) matrix showing intergranular porosity partially filled by a carbonate cement. (C) PPL & (D) XPL views of a clay-rich sandstone showing quartz (Qz), feldspar (Fd) and micas (white arrows) embedded in a red-clay matrix. (E) & (F) PPL views of a clean sandstone displaying quartz (Qz), feldspar (Fd) and a high intergranular porosity partially filled by a carbonate cement (white arrows).**





**Figure 13: Photomicrographs highlighting the different pore types observed in this study, the porosity is in blue. (A) PPL view of a porous sandstone displaying intergranular porosity and molds. The white arrow points to a partially dissolved feldspar. (B) PPL view of a clayed sandstone displaying only microporosity in the matrix. (C) PPL view of a heterogeneous sandstone, displaying intergranular porosity in the upper part and nearly no porosity in the lower part. (D) PPL view of a crystalline dolomite showing Intercrystalline porosity. (E) PPL view of a vuggy porous quartz-rich crystalline dolomite. (F) PPL view of a vuggy porous glaebular and crystalline dolomite.**

### 2.3.3 Paragenetic sequence

The various diagenetic phases, including different types of cement, dissolution events, dolomitization as well as compaction, are described in this section. They are organized chronologically, according to their timing (Figure 14), mainly deduced from crosscutting relationships, observed on cores and thin-sections.

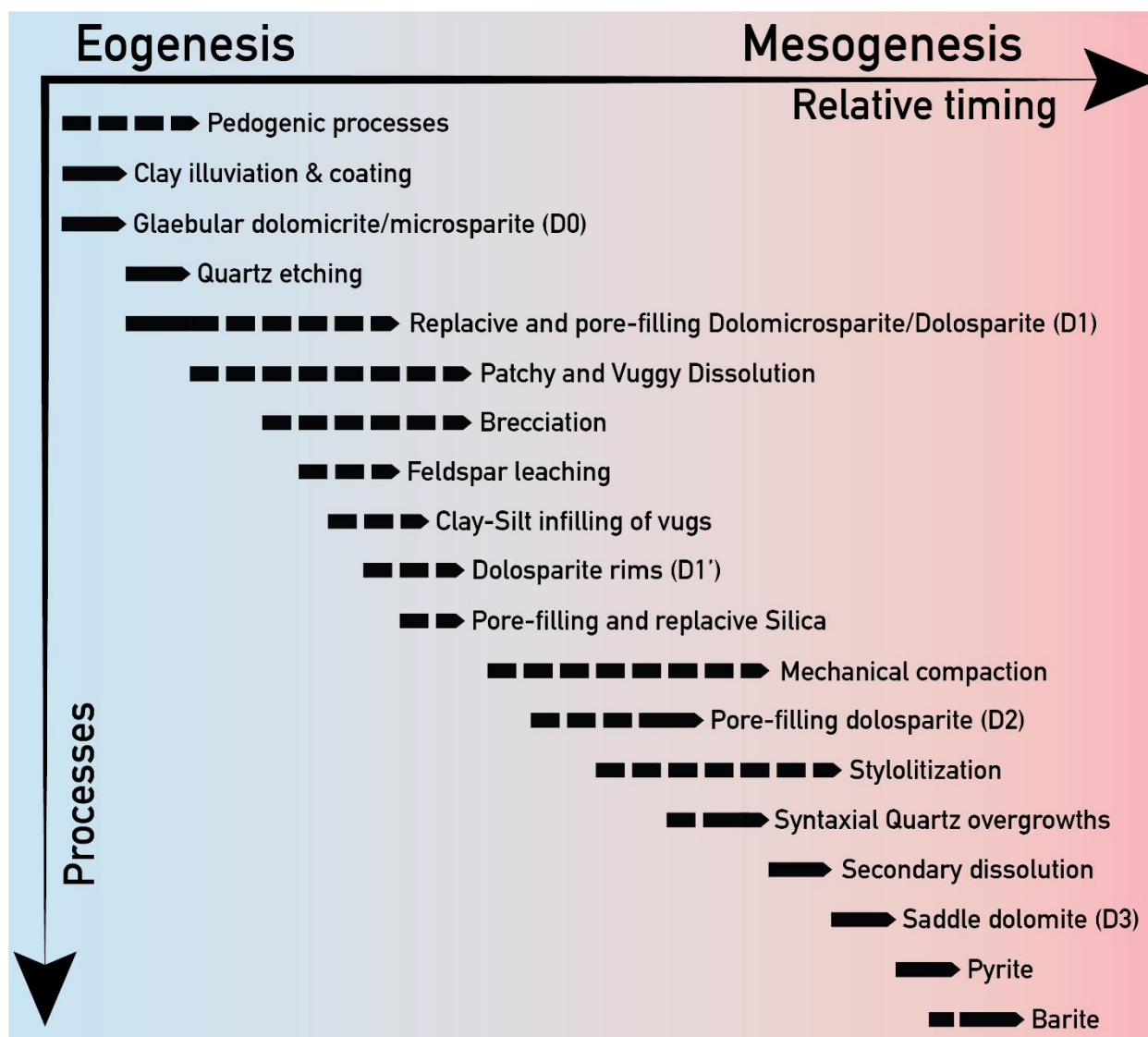


Figure 14: Paragenetic sequence defined in this work, highlighting the relative timing of 18 diagenetic processes characterized during macroscopic and microscopic descriptions.

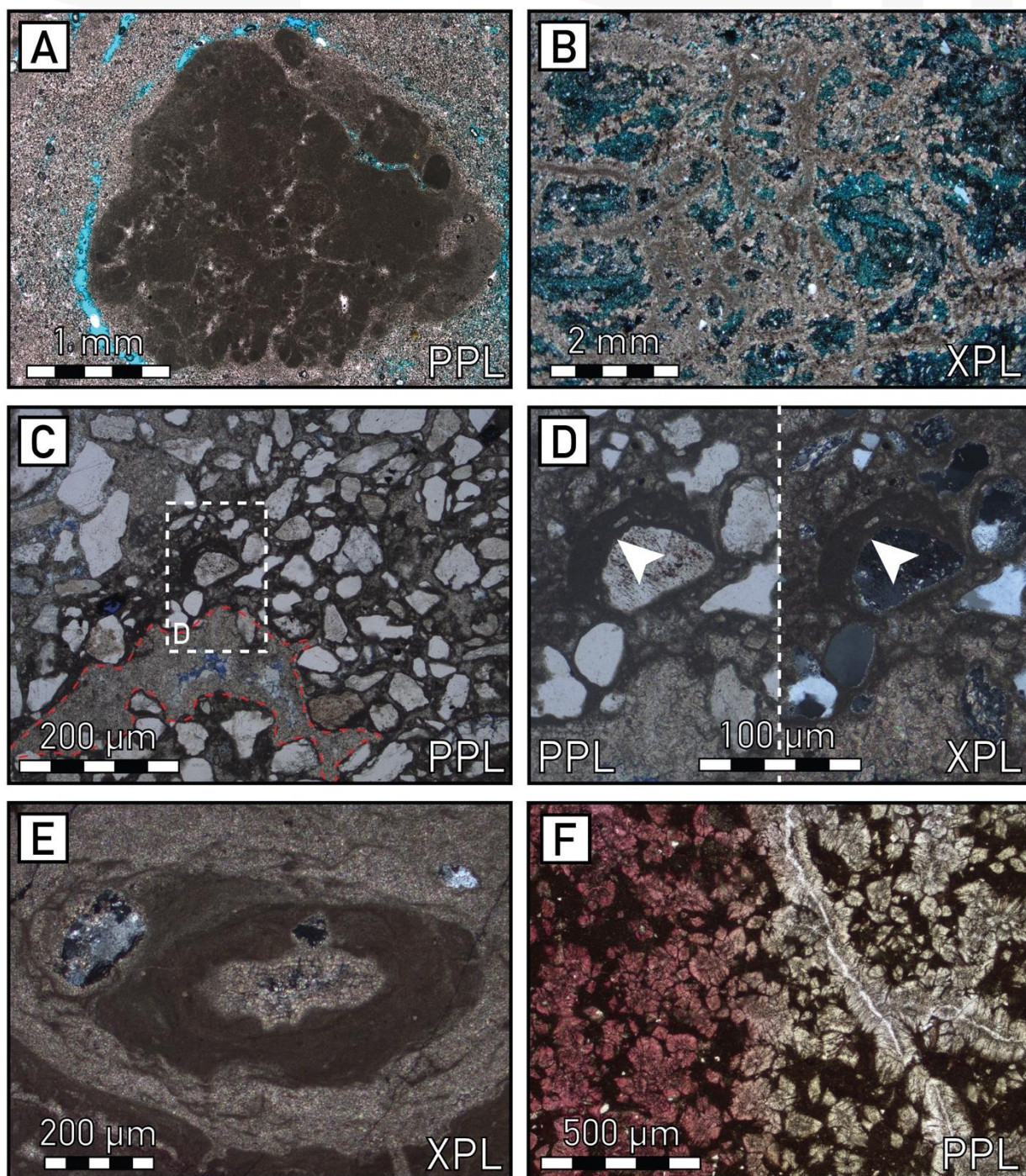


### 2.3.3.1 Pedogenic processes

Pedogenic processes are highlighted by numerous petrographic criteria. As showed previously, macroscopic observations of cores aim to recognized centimeter-size nodules (facies Dn, Figure 9D-F.) and microscopic characterization allow us to observe millimeter-size nodules (Figure 15A), namely glaebules in the sense of Brewer and Sleeman (1964). These glaebules are composed of dolomicrite, they may float in a dolomicrospar matrix (Figure 17A) or coalesce (Figure 16A and Figure 17B), displaying a wide variety of nature (dolomicrite, dolomicrospar with or without quartz content), sizes (infra- to pluri-millimeter), shapes (well-rounded to subangular) and boundaries (sharp to smooth). We further characterized rhizoliths (organo-sedimentary structures produced by roots sensu Klappa, 1980). These structures may form networks, recognized both using microscopic (Figure 15B, F) and macroscopic observations Figure 24A). They developed in a clay-silt matrix and exhibit most of the time a dolomite mineralogy. Nevertheless, one sample presents calcite rhizoliths (Figure 15F), suggesting primary calcite-type mineralogy. Another striking pedogenic criteria is the occurrence of (dolo?)micrite coatings developed around detrital grains (Figure 15C,D), forming heterogeneous networks. According to previous studies (Alonso-Zarza et al., 1992, Alonso-Zarza, 2003), such pedofeatures may contain fungal filaments, clearly suggesting an activity of micro-organisms, to put in relation with carbonate precipitation. For approving this hypothesis, further investigations using scanning electron microscopy are required. Last but not least, alveolar septal structures may occur. Following Alonso-Zarza (2003), they correspond to ‘arcuate micrite septae’ (in the sense of Adams, 1980) and develop within pores or border the root traces (Klappa, 1980). Indeed, we observed alveolar septal structures around the transverse cross section of a root (Figure 15E). All these pedofeature criteria clearly indicate a pedogenic activity affecting the studied rocks during eogenesis (early diagenesis sensu Choquette & Pray, 1970, occurring in the first meters of the sedimentary column, below the air-sediment interface for the vadose environment, and below the sediment-water interface for the phreatic environment).

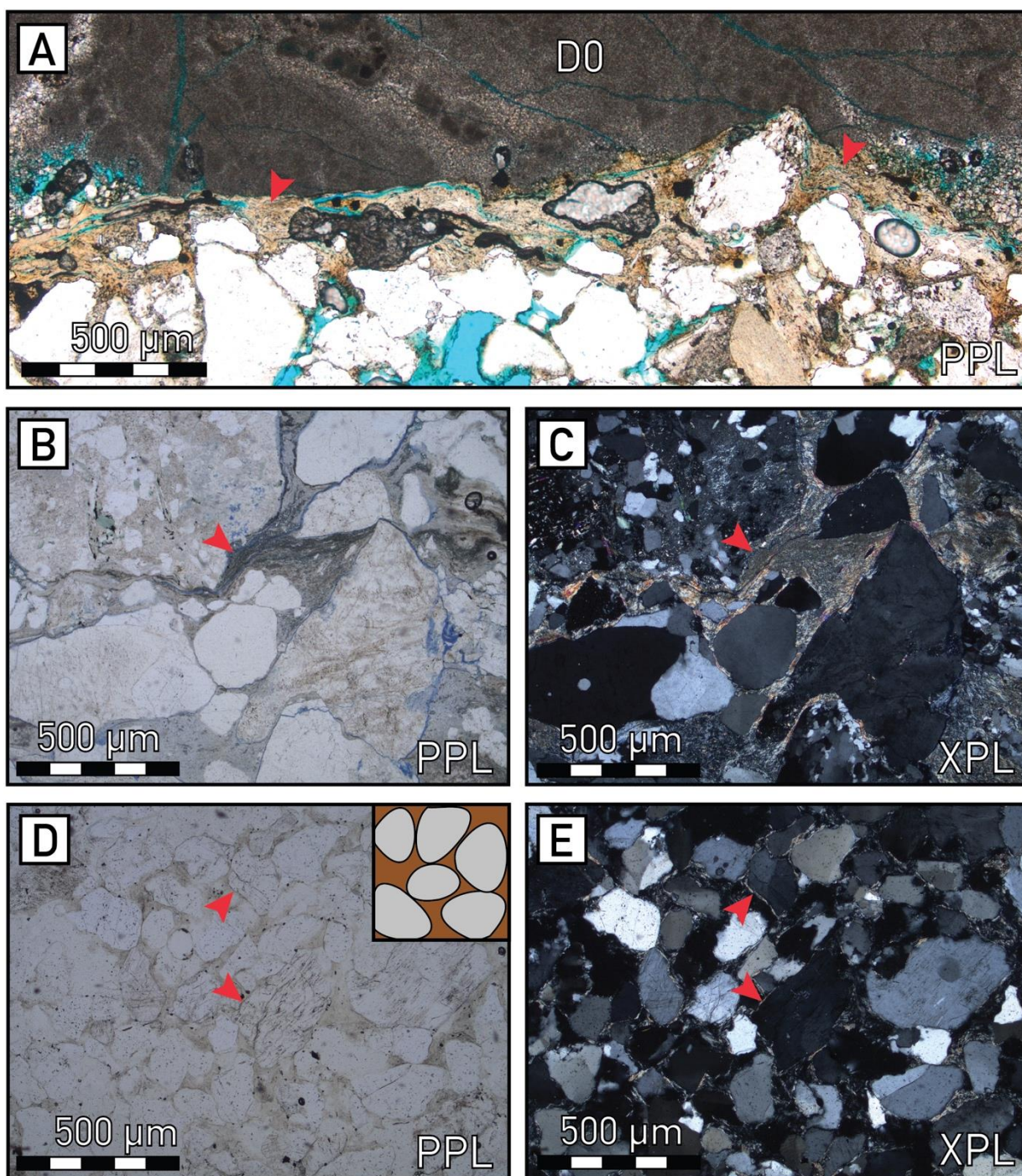
### 2.3.3.2 Clay illuviation & coatings

Another diagenetic process identified in thin-sections gather illuviation and coating of clays, indicating an early infiltration of clays within the sediments (Figure 16). Indeed, we observed dusty to limpid well crystallized clays comprising microlaminations and showing a contorted aspect (Figure 16A-C). These clays may also coat the detrital grains (Figure 16D-E, tangential clays in the sense of Worden & Burley, 2003). Such clays may inhibit the diagenetic potential of sandstones by blocking possible subsequent overgrowths of quartz, potentially preserving porosity (*e.g.* Ajdukiewicz & Larese, 2012). They correspond to the so called ‘clay cutans’ of Brewer (1960), resulting from mechanical infiltration during eogenesis, prior to mesodiagenesis and compaction. According to Spötl (1991), these clays correspond to illite.



**Figure 15: Photomicrographs of the main pedogenic features identified in thin sections. (A) PPL view of a dolomicrite glaeble highlighting a circum-granular porosity, surrounded by a tight groundmass dolomicrosparite. (B) XPL view of a rhizolith network (*sensu* Klappa, 1980) embedded in a clayed and silty microporous matrix. (C) PPL view of a dolomicrite coating developed around detrital grains. The red dashed line indicates a former pore presently cemented by a dolomicrospar/dolospar. (D) PPL and XPL views of an asymmetrical dolomicrite coating (not to be confounded with a pendant cement) developed around a rounded feldspar (white arrow). Note that the micrite network mimics the geometry of alveolar septal structures. (E) PPL view showing a transverse cross section of a dolomitized root. It highlights concentric alveolar septal structures together with a detrital grain partially cracked and replaced by dolomicrospar. (F) PPL view of pink-colored calcite displaying a rhizolith framework developed within a clayed matrix.**





**Figure 16: Photomicrographs of clay-related diagenetic processes. (A) PPL overview of illuvial clays (probably illite, red arrows) accumulated between a tight dolomicrite groundmass level (D0) and a porous sandy level. (B) PPL and (C) XPL views of illuvial clays (probably illite, red arrow) developed between detrital grains. (D) PPL and (E) XPL views of a clayed sandstone, highlighting numerous clay coatings developed around quartz and feldspar grains (red arrows).**

### 2.3.3.3 Dolomicrite and dolomicrosparite (D0)

Dolomicrite (D0) corresponds to the earliest carbonate phase observed in this work (Figure 14), corresponding to very small crystals ( $\leq 4 \mu\text{m}$ ) forming the glaebules, appearing brownish in PPL (Figure 17A). Under CL, D0 is characterized by a wide spectrum of colours, including bright orange (Figure 17B), dull brown colour and sometimes poorly-luminescent (Figure 20D,E) with a peloidal aspect outlined by differences in luminescence intensity. Such a CL intensity variation outlines an early polycyclic formation of dolomicrite. Furthermore, recrystallization of dolomicrite may occur (here probably aggrading neomorphism in the sense of Folk, 1965), inducing the development of dolomicrosparite (crystal size  $\leq 20 \mu\text{m}$ , Figure 17C) easily recognizable under PPL (fogged mosaic of inequigranular crystals *sensu* Randazzo & Zachos, 1983). Under CL, dolomicrosparite exhibits a darker colour than dolomicrite, namely dull orange to dull brown (Figure 17D). According to quantitative EDS and microprobe analyses of Spötl (1991), this early dolomite is non ferroan.

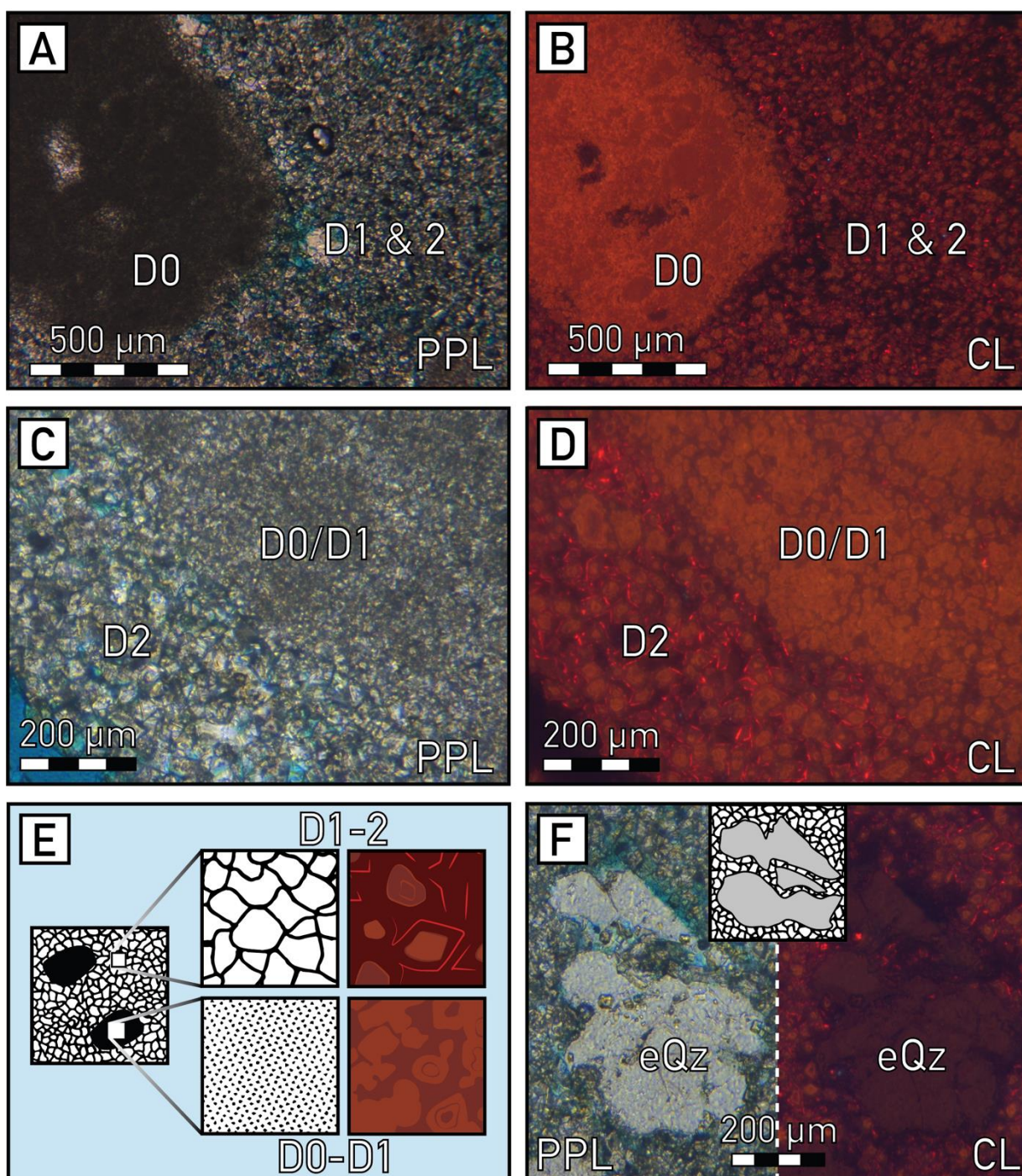
### 2.3.3.4 Dolomicrosparite & dolosparite 1 (D1)

Dolomicrosparite ( $\leq 20 \mu\text{m}$ ) and dolosparite 1 (D1, up to  $50 \mu\text{m}$ ) is the widest cement observed in this work. This dolomite phase is a continuum of the dolomicrosparite previously presented in section 2.3.3.3 (Figure 14). It is highly replacive (Figure 17C) and also pore-filling (Figure 20D-F). In the sense of Randazzo & Zachos (1983), D1 shows a variety of textures under PPL and XPL, including i) equigranular sutured mosaic texture (Figure 13D), equigranular sieve mosaic texture (Figure 17A and Figure 20A), inequigranular fogged mosaic texture (Figure 17C), inequigranular porphyrotopic texture with contact-rhomb and floating rhombs (Figure 18E-F). It may also rarely exhibit lenticular and 'rice-shaped' (*sensu* Spötl, 1993) sutured or floating euhedral crystals (Figure 24C,D) forming centimeter-scale rhizolith frameworks (Figure 24A,B). Under CL, D1 displays a wide variety of colours and intensities, including dull brown (Figure 17B,D) and dull to bright orange (Figure 18C & Figure 20D-F). Such a multifaceted CL signature attests of a polycyclic replacement and cementation of D1, underlying probably fluctuating environmental conditions. Note that quartz-rich dolomite shows fractured and etched quartz (Figure 17F), attesting of a partial replacement (see Wright & Tucker, 1991). According to SEM investigations of Spötl (1991), D1 is non ferroan.

### 2.3.3.5 Dolosparite rims (D1')

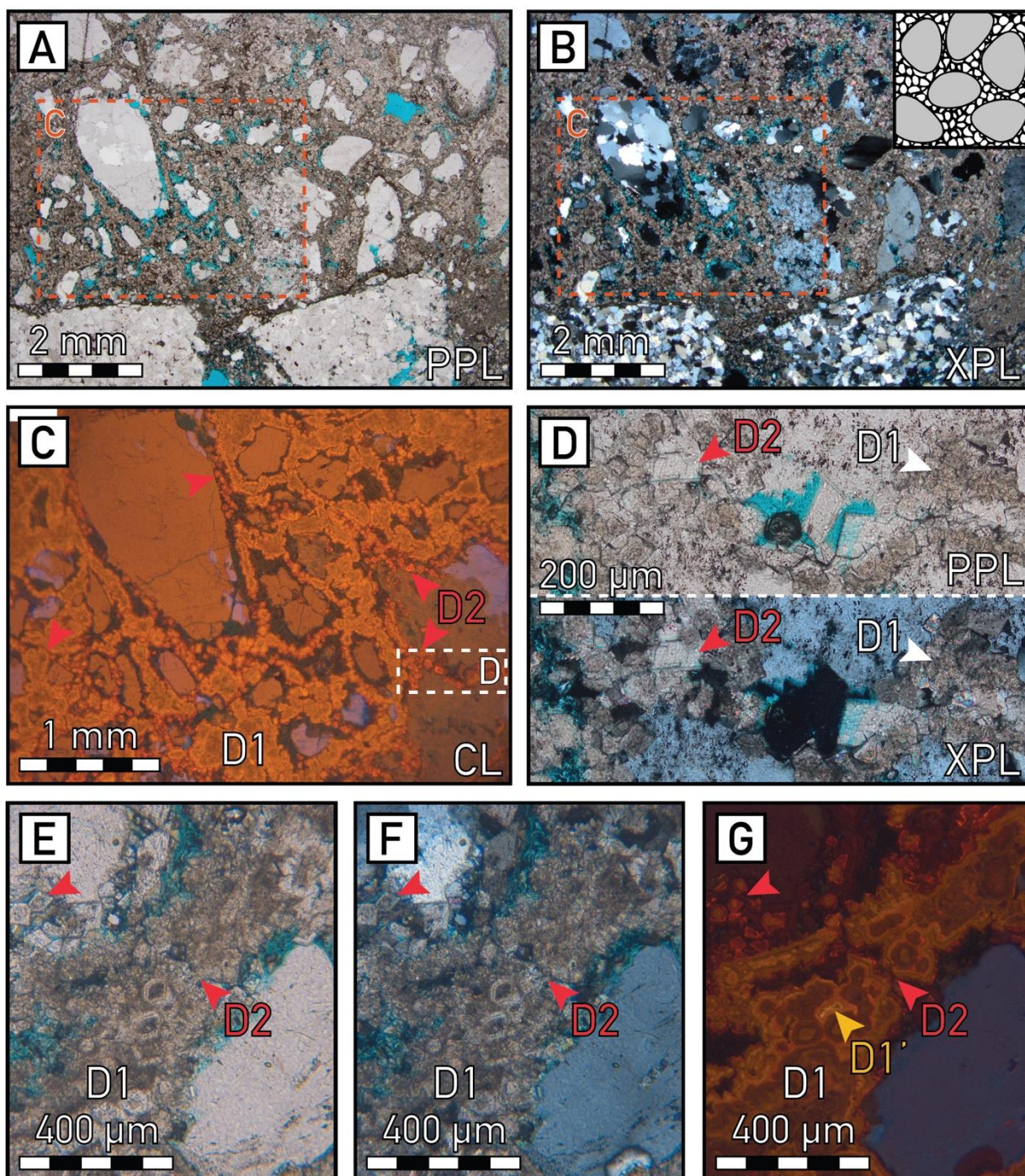
Dolosparite rims (D1') are only recognizable using CL investigations, they are postdating D1 (Figure 14). Under CL, D1' displays a distinct bright to very bright yellow colour, corresponding to micrometer-scale euhedral overgrowths on D1 (Figure 18G, Figure 20E, Figure 22D,F). D1' is a pore filling cement, mainly observed on dolomite samples. In a few examples, it may show several growth stages (Figure 24B, D). According to microprobe analyses of Spötl (1991), the intense yellow colour in CL is due to high Mn-concentrations (around 1-3mole-% of  $\text{MnCO}_3$ ).





**Figure 17: Photomicrographs of early dolomite cements. (A) PPL and (B) CL views of dolomicrite glaeboles (bright orange D0) and replacive and pore-filling dolomicrosparticle/dolosparite (dull brown D1 and non-luminescent with thin bright red bands D2). (C) PPL and (D) CL views of early cements, including dolomicrite, dolomicrosparticle and dolosparite (D0, D1 and D2). (E) Sketches representing the early dolomite cement, namely D0/D1, observed in association with glaeboles and replacive/pore-filling D1/D2. (F) PPL and CL views of a fractured and etched quartz grain partially replaced by dolomite microcrystals (D1/D2).**





**Figure 18: Photomicrographs of early dolomite affecting conglomerates and sandstones. (A) PPL and (B) XPL views of a sandstone cemented by a dolomicrosparite/dolosparite, displaying molds (dissolved feldspar?) and rimmed porosity around detrital grains (mono- and polycrystalline quartz mainly). Note the occurrence of intragranular porosity suggesting a dissolution event. (C) CL view referring to the dashed orange insert in A and B, showing patches of dull to bright orange dolosparite (D1) displaying bright red overgrowths (D2, red arrows). (D) PPL and XPL views referring to the dashed white insert in C, highlighting replacive cloudy (D1) to limpid euhedral (D2) dolomite. Note the occurrence of porosity that mimics rhomb shape of dolomite, suggesting a partial dissolution. (E) PPL, (F) XPL and (G) CL views of a polycyclic dolomite replacement and cementation (D1, D1' and D2) in a sandstone. D1' occurs as a fine dull yellow overgrowth on D1/D2.**

### 2.3.3.6 Patchy and vuggy dissolution, brecciation

Both macroscopic and microscopic investigations outline the occurrences of millimeter- to centimeter-scale vuggy pores affecting dolomites (Figure 19A, D and Figure 20A, C). Such pores may remain open but may also be filled by green silts and clays or cements and are closely associated with brecciation processes (Figure 19B, C). This dissolution phase clearly affects the early dolomites, as attested by the corrosion phase outlined by CL (for example, see D1 on Figure 18G) and the post-dating infill by sediments and cements (Figure 19B). Furthermore, D1' may locally postdate this dissolution event, as highlighted by its pore-lining geometry (Figure 20E and Figure 22D, F). Moreover, dissolution predates silica cementation and replacement as vugs and intercrystalline pores may be filled by silica (Figure 21 and Figure 22). The relative timing of this phase is thus difficult to determine accurately and we propose a general early and polyphased event (Figure 14) occurring in close relationships with replacive and pore-filling dolomite (D1, D1') and silica.

### 2.3.3.7 Silica replacement and cementation

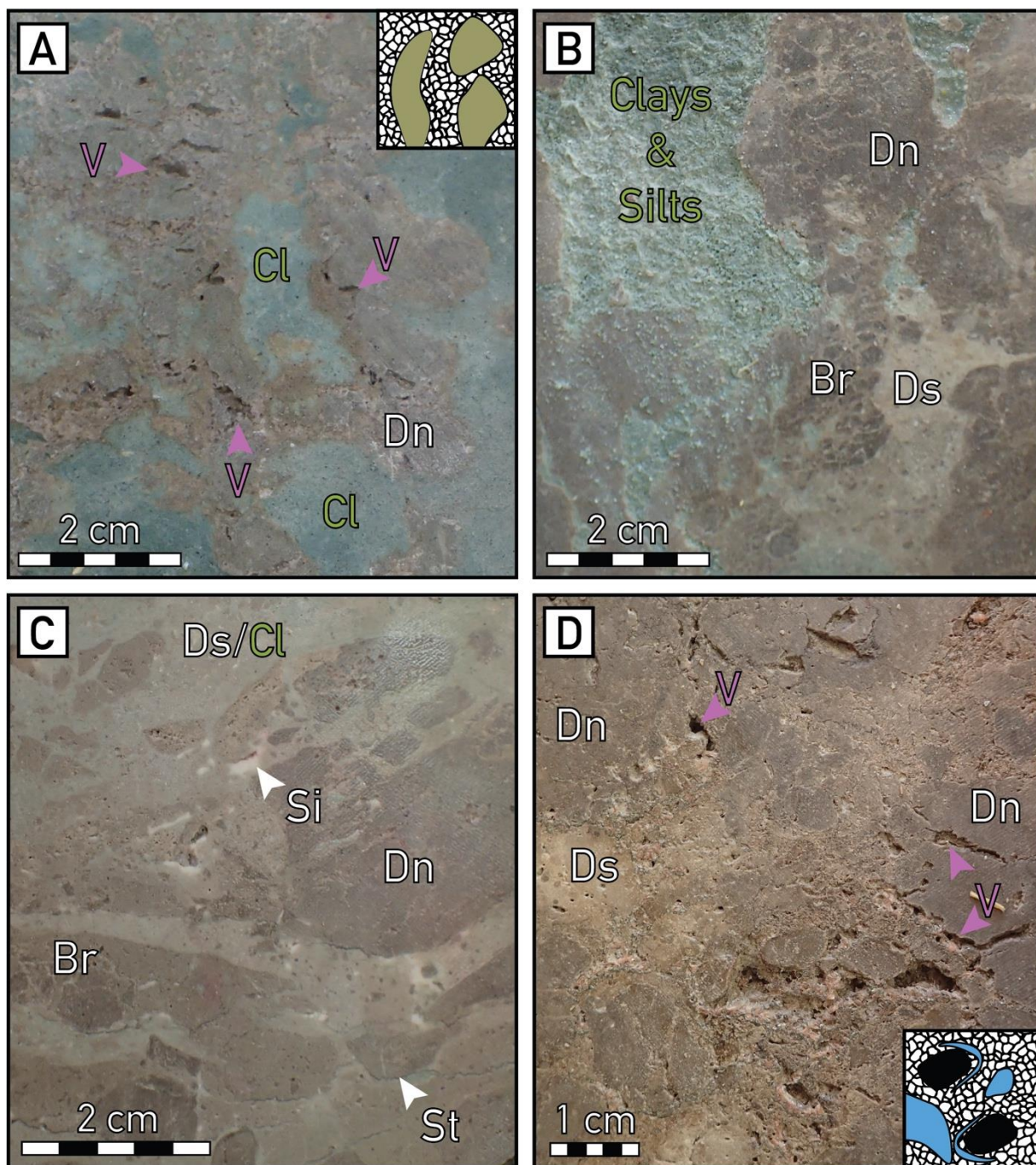
Silica is locally distributed in dolomite, it is easily recognizable on cores as it displays a milky texture (Figure 19C). It occurs as both pore-filling (Figure 21A,B, Figure 22C) and replacive (Figure 21F). Microscopically, silica is polyphased, showing a wide spectrum of textures (Figure 21A-B), including chronologically: i) microquartz cement ( $\mu\text{Qz}$ ), ii) chalcedony cement (botryoidal and spherulites, *i.e.* length-fast and length-slow chalcedony, Spötl & Wright, 1992) and prismatic megaquartz cement. Note that silica cement may contain early dolomite crystals, floating in microquartz (Figure 21A,B and Figure 22D-F) or acting like cores of chalcedony spherulites (Figure 21D), often associated with a peculiar porosity that rims the floating dolomites or affects some chalcedony layers. Such porosity probably developed during the early dissolution event; but we cannot exclude a subsequent dissolution phase. Under CL, silica is non-luminescent and clearly postdates D1' (Figure 22D, F). Furthermore, note that some microquartz display a microbreccia floating texture within dolomicrite (Figure 21D, E), further supporting an early silica cementation and replacement event.

### 2.3.3.8 Dolosparite 2 (D2)

Dolosparite 2 (D2) is a pore-filling cement widely observed in thin-sections, affecting both dolomites and sandstones. Following the Randazzo & Zachos (1983) classification, limpid D2 mostly displays an equigranular sutured mosaic under PPL (Figure 18D, Figure 20F and Figure 24C,D). Under CL, D2 clearly occurs as overgrowths on D1 and D1' and displays non-luminescent zone containing thin bright to dull red bands (Figure 20D-F and Figure 24B-D). Note that a few CL observations suggest a recrystallization associated with D2, as bright red patches may be locally observed within a dull to bright orange dolomite (Figure 22F). D2 is clearly postdating the early dissolution event and may locally contribute to the replacement of detrital quartz (Figure 18C-G). Its homogeneous texture and CL pattern obviously point to a single cementation event

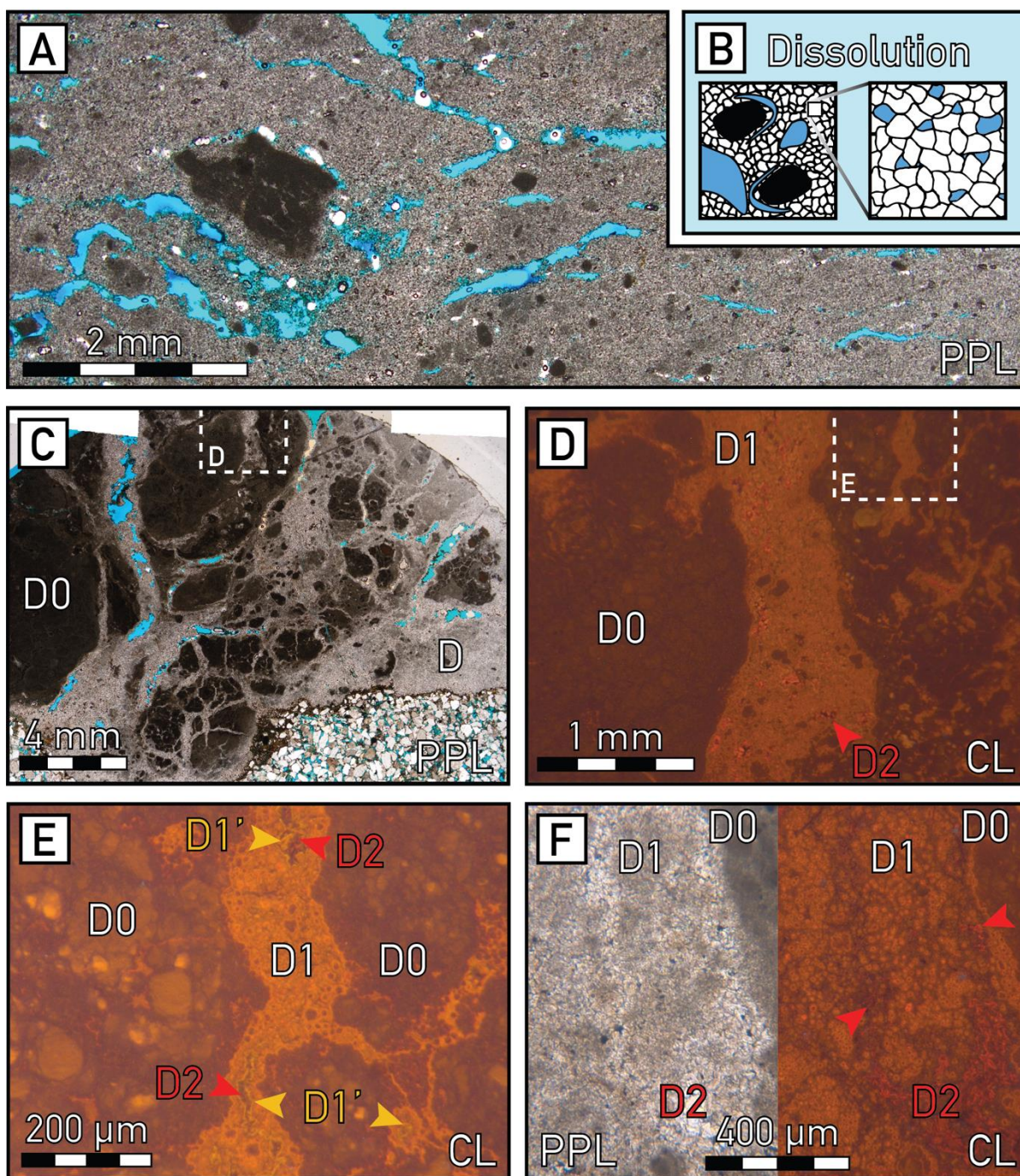


probably occurring during mesodiagenesis (Figure 14). According to SEM investigation of Spötl (1991), D2 is slightly ferrous.



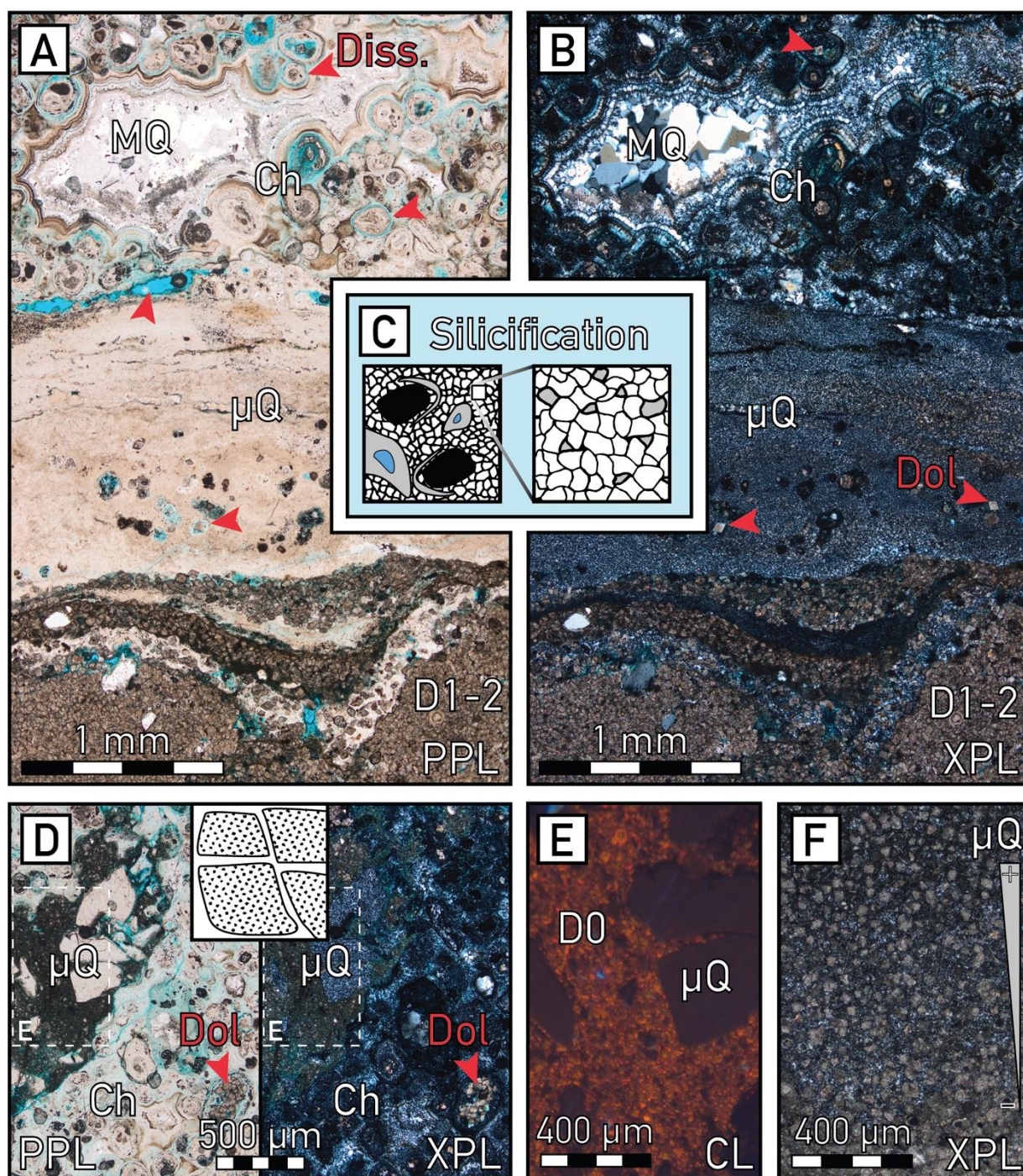
**Figure 19: Macroscopic characterization of dolomite diagenesis. (A) Macroscopic view of a well-developed nodular dolomite (Dn) within clays (Cl), displaying numerous vugs (V). (B) Macroscopic view of a nodular (Dn) and brecciated (Br) dolomite showing formerly large pores, presently infilled by dolosparite (Ds) and greenish clays and silts. (C) Macroscopic view of a homogeneous massive dolomite showing dolomicrite nodules (Dn), breccia (Br), matrix (Ds/Cl), milky silica (Si) and stylolites (St) mainly affecting the matrix. (D) Macroscopic view of a massive nodular dolomite, showing vuggy (V) dolomicrite (Dn) and dolosparite (Ds) probably replacive or pore-filling.**





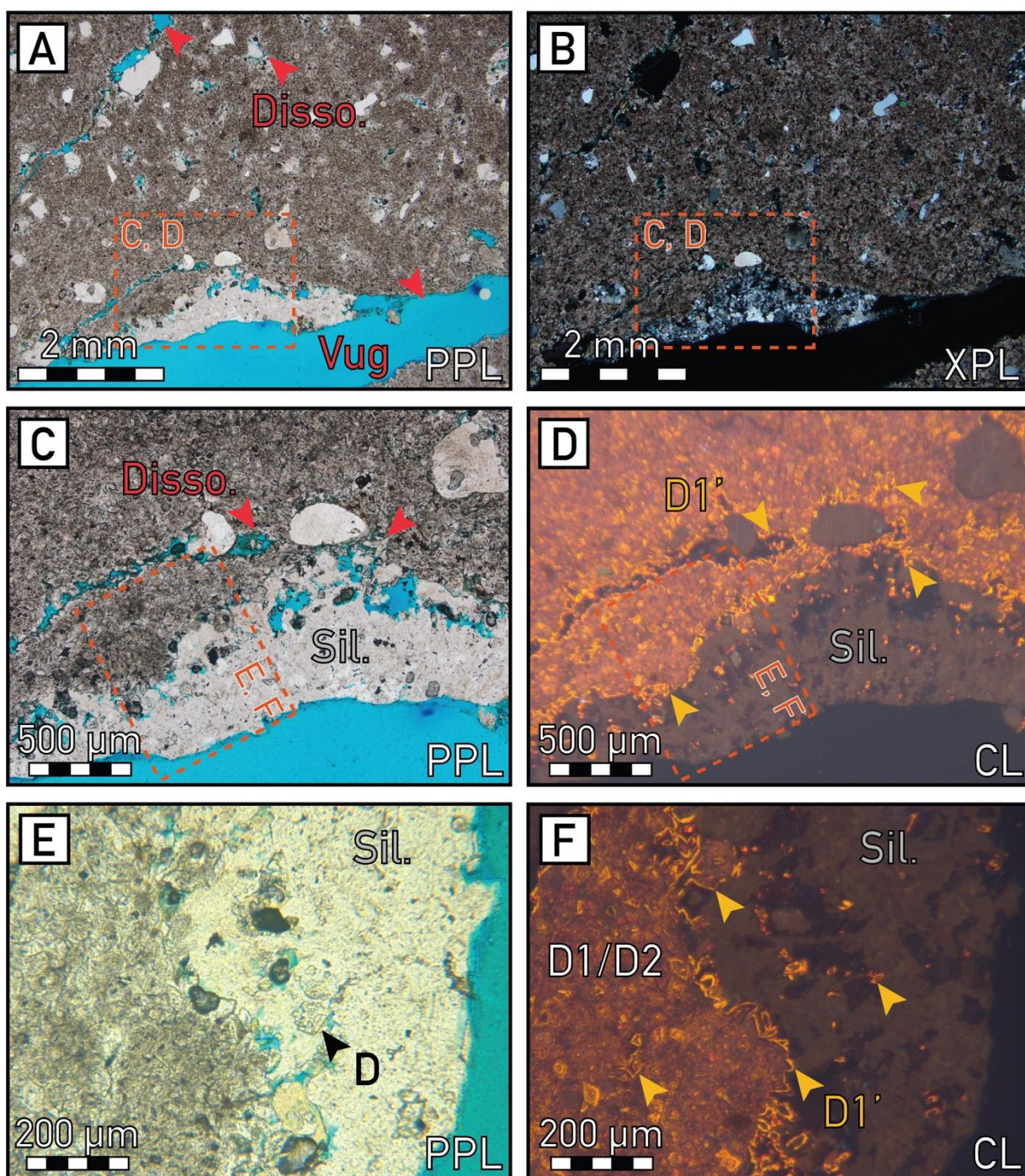
**Figure 20: Photomicrographs of dissolution events and dolomite cementation. (A)** Enlarged PPL view of a clay-free vuggy dolomite, displaying linear and curved millimeter-size vugs affecting dolosparite. **(B)** Sketches highlighting the dissolution of dolosparite. **(C)** Enlarged PPL view of dolomicrite glaebules (D0) and dolosparite (D) overlying a porous sandstone. **(D)** CL view of the white dashed insert in (C), displaying a very poorly luminescent dolomicrite (D0), a dull orange dolosparite (D1) and a bright red dolosparite (D2). **(E)** CL view of the white dashed insert in (D), displaying poorly luminescent to dull orange dolomicrite (D0), and a polycyclic pore-filling cement, including dull to bright orange dolosparite (D1), thin bright yellow dolosparite (D1') and non-luminescent with thin bright red bands dolosparite (D2). **(F)** PPL and CL views of poorly-luminescent dolomicrite (D0), poorly-luminescent to dull orange dolomicrosparite (D1) and limpid non-luminescent with thin bright red bands dolosparite (D2).





**Figure 21: Photomicrographs of silicification processes. (A) PPL and (B) XPL enlarged views of a polycyclic silicification affecting dolosparite; massive microquartz ( $\mu$ Q) including floating rhombs (Dol) showing a rimmed porosity (red arrows), a polycyclic chalcedony (Ch) showing porous bands (red arrows) and a pore-filling megaquartz (MQ). (C) Sketches highlighting the pore-filling and replacive silicification. (D) PPL and XPL views of microquartz breccia ( $\mu$ Q) floating in a dolomicrite, together with a patchy porous chalcedony (Ch) preserving punctually dolosparite 'cores' (Dol). (E) CL view of the white dashed inserts in (D), showing non-luminescent microquartz ( $\mu$ Q) and poorly-luminescent to bright orange dolomicrite (D0). (F) XPL view of an aggrading silicification affecting dolomite rhombs.**





**Figure 22: Photomicrographs of dissolution and cementation events. (A) PPL and (B) XPL views of vuggy dissolution affecting a quartz-rich dolomite (red arrows), postdated by a polycrystalline quartz cement. (C) PPL and (D) CL views of the orange inserts in (A) and (B), displaying a dull orange dolosparite, thin bright yellow bands of dolosparite (D1', yellow arrows) lining the porosity (red arrows) and predating silica (Sil). (E) PPL and (F) CL views of the orange inserts in (C) and (D), displaying dull orange dolomicrospar to dolospar with bright red patches (D1/D2) pore lining thin bright yellow bands of dolosparite (D1', yellow arrows) and porous silica (Sil) with dolomite remnants (D, black arrow in PPL and yellow arrow in CL).**



### **2.3.3.9 Mechanical compaction & syntaxial quartz overgrowths**

According to microscopic characterization, mechanical compaction of sandstones may locally occur but is probably controlled by predating early dolomite cementation and clay illuviation processes. Indeed, some quartz-rich dolomites display a tight texture due to dolomite cementation (mainly D1) that may greatly inhibit the mechanical compaction (Figure 18A and Figure 23A). Nevertheless, several examples of porous sandstones display evidences of mechanical compaction and syntaxial quartz overgrowths (QO, Figure 23B-D). Interestingly, these QO may contain small floating D2 rhombs (Figure 23E, F). Such petrographic evidences point to a joint cementation of D2 and QO during mesodiagenesis (Figure 14).

### **2.3.3.10 Secondary dissolution of dolomite cement**

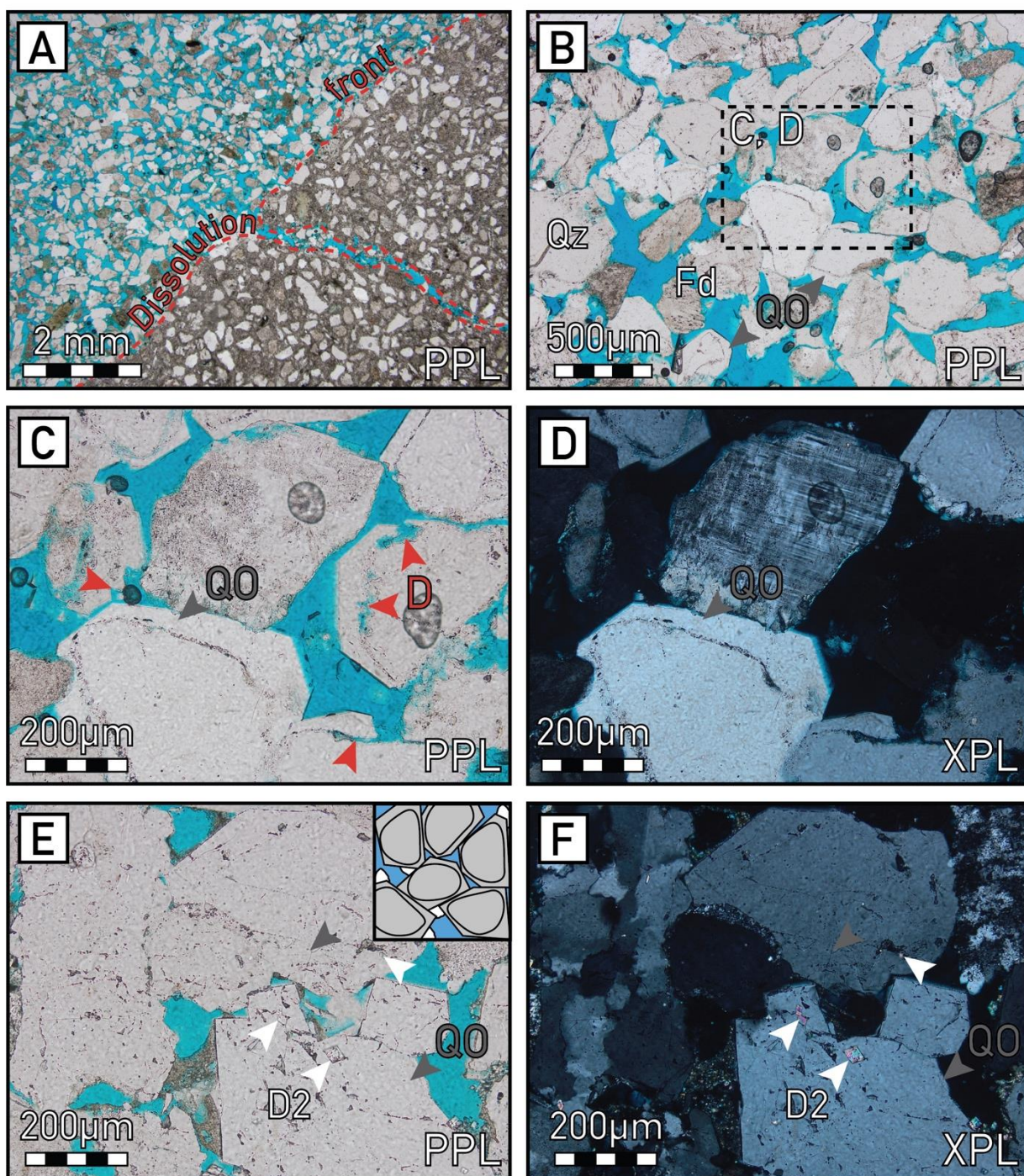
Petrographic observations highlight evidences of a secondary dolomite dissolution event. Indeed, floating detrital grains may be microscopically observed, associated with dissolution fronts (Figure 23A). Given that the studied rocks subside down to 2 km depth, such floating texture must correspond to a late dissolution and did not occur during early diagenesis. Furthermore, the porous pattern highlighted by quartz overgrowth also points to this conclusion (pores between detrital quartz and quartz overgrowth and molds of dolomite rhombs, Figure 18D and Figure 23C). Thus, all these petrographic criteria clearly support a secondary dissolution event, potentially affecting early (D0, D1, D1') and late (D2) dolomite.

### **2.3.3.11 Saddle dolomite (D3)**

Microscopic observations aim to identify late saddle dolomite (D3), corresponding to pore-filling limpid euhedral crystals with a cloudy core (Figure 24E). Under XPL, D3 shows an undulatory extinction (Figure 24E). Under CL, D3 is non-luminescent and corresponds to overgrowths on predating D1 and D2 (Figure 24F). Its cloudy core matches with earlier dolomite phases. Following the earlier work of Spötl (1991), D3 displays a chemical zonation with an increasing Fe content from the core towards the rim, corresponding thus to Ca-enriched ferroan dolomites.

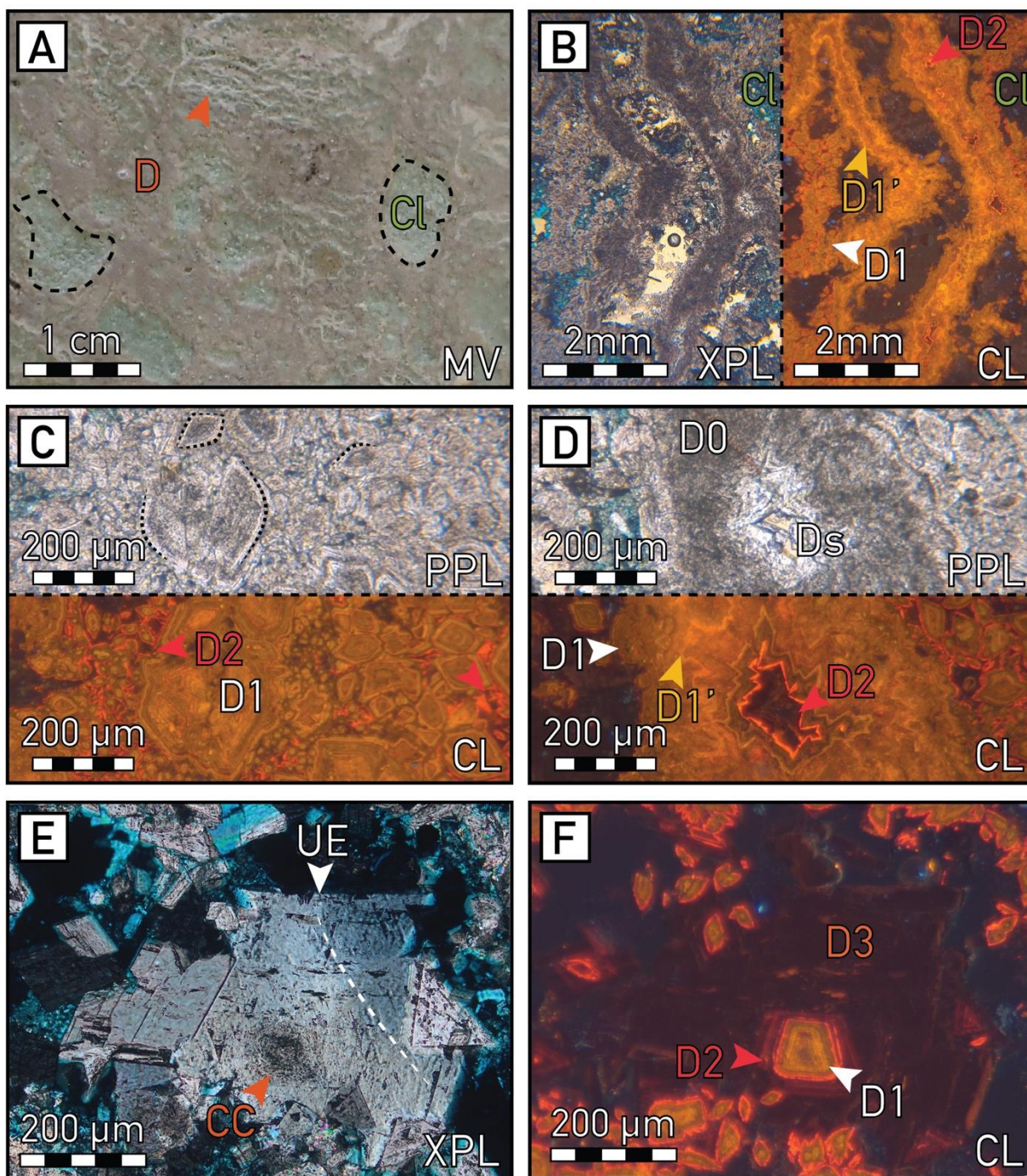
### **2.3.3.12 Chemical compaction & barite/pyrite cementation**

Macroscopic observations of dolomite cores point to local chemical compaction processes (stylolites) associated with late-stage vug-filling sulphates (barite) and sulphide (pyrite) cements (Figure 25A-C). Under PPL, barite shows radiaxial dirty crystals containing small inclusions and floating dark pyrites (Figure 25D). XPL and RL observations further confirm the barite and pyrite occurrence (Figure 25E,F). Few samples display also pore-filling celestine cement.



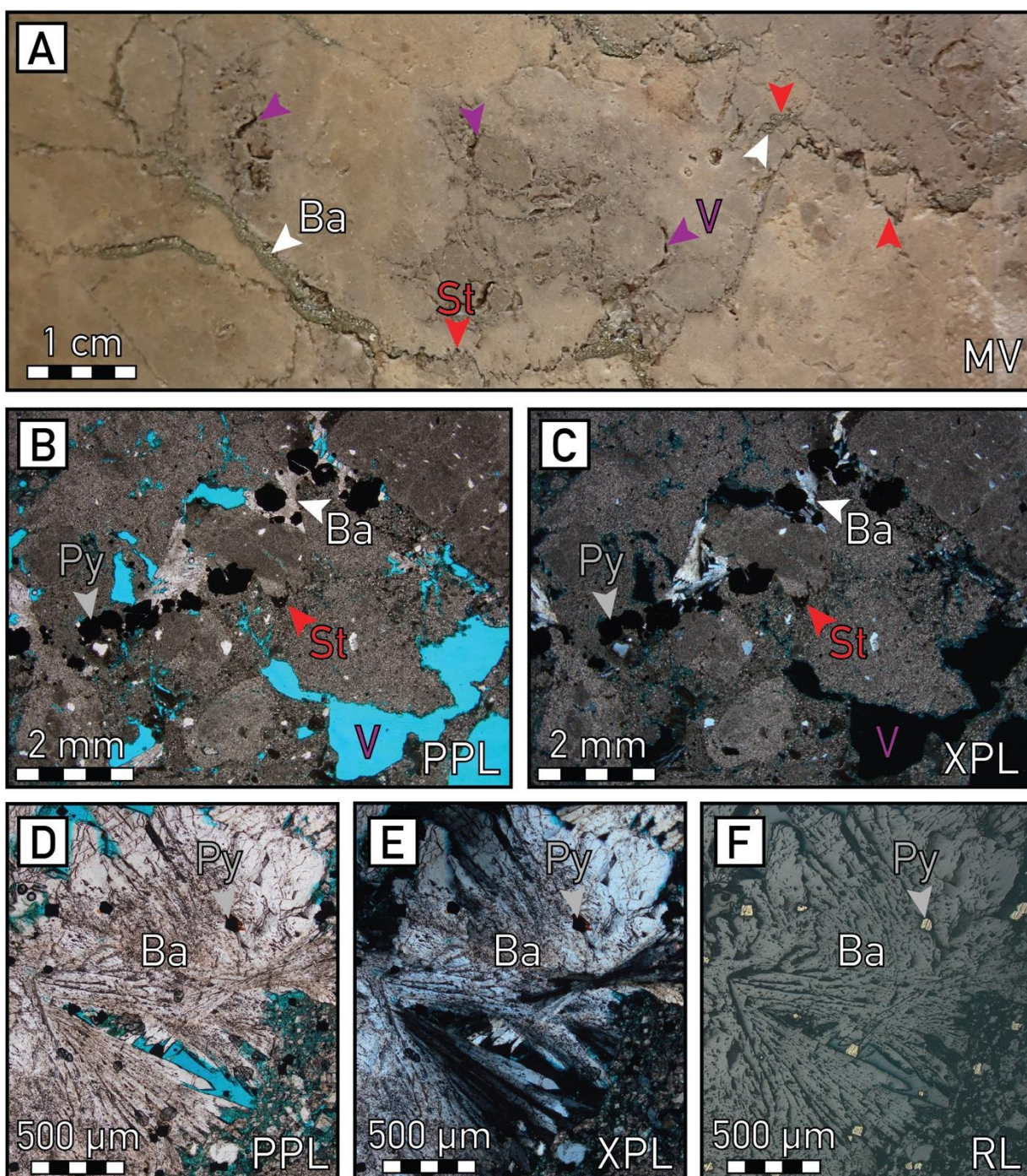
**Figure 23: Photomicrographs of dissolution evidence, mechanical compaction and quartz overgrowths. (A) PPL view of dissolution affecting the dolomicrosparite of a quartz-rich dolomite, inducing a highly porous floating-quartz/feldspar texture. (B) PPL view of a highly porous sandstone displaying subrounded quartz (Qz) and feldspar (Fd) and quartz overgrowth (QO, grey arrows). (C) PPL and (D) XPL views of the dashed black insert in (B), showing evidence of dissolution (D, red arrows) between quartz and quartz overgrowths (QO, grey arrows), punctually mimicking the rhomb shape of dolomite. (E) PPL and (F) XPL views of dolomite remnants (D2, white arrows) observed in the quartz overgrowths (QO, grey arrows).**





**Figure 24: Macroscopic views and photomicrographs of the dolomite cements identified in this work. (A)** Macroscopic view of a clay-rich dolomite, showing a rhizolith framework (D, orange arrow) together with centimeter-size rounded clay patches (black dashed lines, CI). (B) XPL and CL views of the rhizolith framework developed within clays (CI), displaying a polycyclic dolomite cementation, including dull to bright orange dolomicrospar to dolospar (D1), bright yellow thin bands of dolomite (D1') and limpid non-luminescent and bright red bands of dolosparite (D2). (C) PPL and CL views of 'rice-shaped' bright to dull orange dolomite with cloudy core and limpid rims (D1) and limpid, bright red dolomite overgrowths (D2, red arrows). (D) PPL and CL views of the polycyclic dolomicrospar (D0) and limpid dolosparite (Ds) including the same dolomite generations as (B), namely D1, D1' and D2. (E) XPL and (F) CL views of saddle dolomite, including a cloudy core (CC, orange arrow) corresponding to bright to dull orange dolomite (D1), non-luminescent with thin bright red bands dolomite (D2), and inclusion-rich limpid overgrowth displaying a non-luminescent (D3) with an undulatory extinction (UE, white arrow and dashed line).



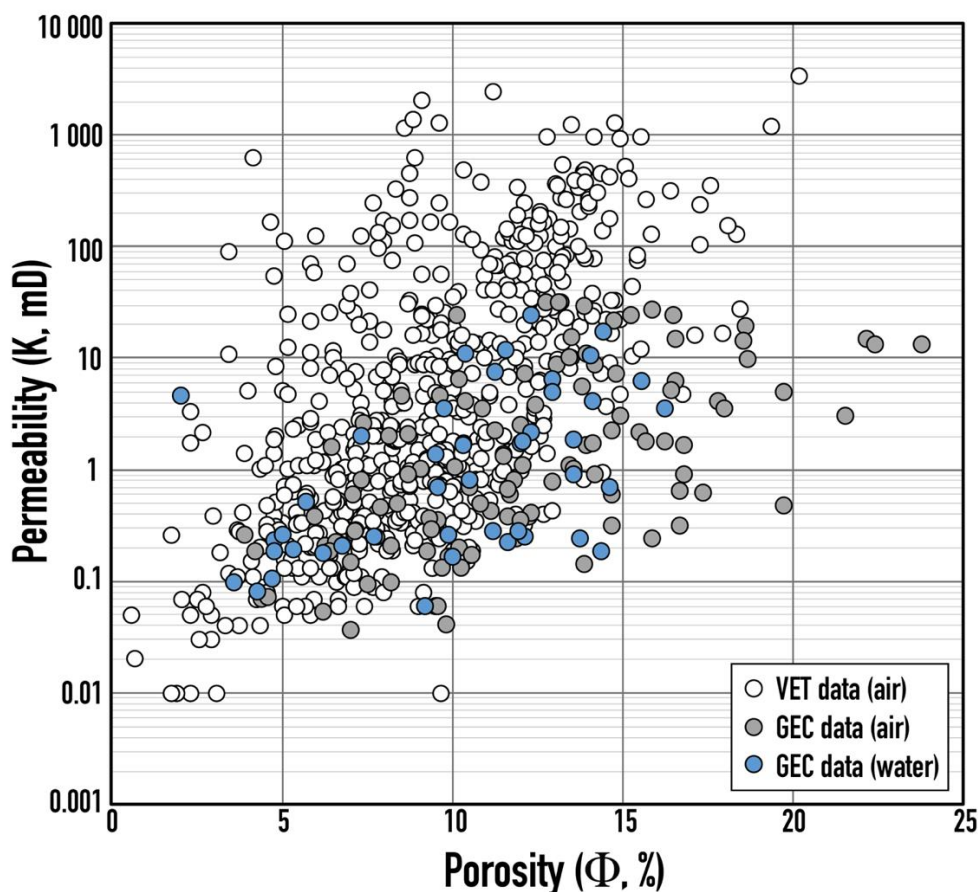


**Figure 25: Macroscopic and microscopic views of chemical compaction and related cement phases.** (A) Macroscopic enlarged view of stylolites (St, red arrows) affecting a massive dolomite, vuggy pores (V, violet arrows) and barite cementation (Ba, white arrows). (B) PPL and (C) XPL views of vuggy pores, stylolites (St, red arrows), Barite (Ba, white arrows) and Pyrite (Py, grey arrows) cementation. (D) PPL, (E) XPL and (F) RL views of Barite cement (Ba), with small Pyrite inclusions (Py, grey arrows).



### 2.3.4 Petrophysical results

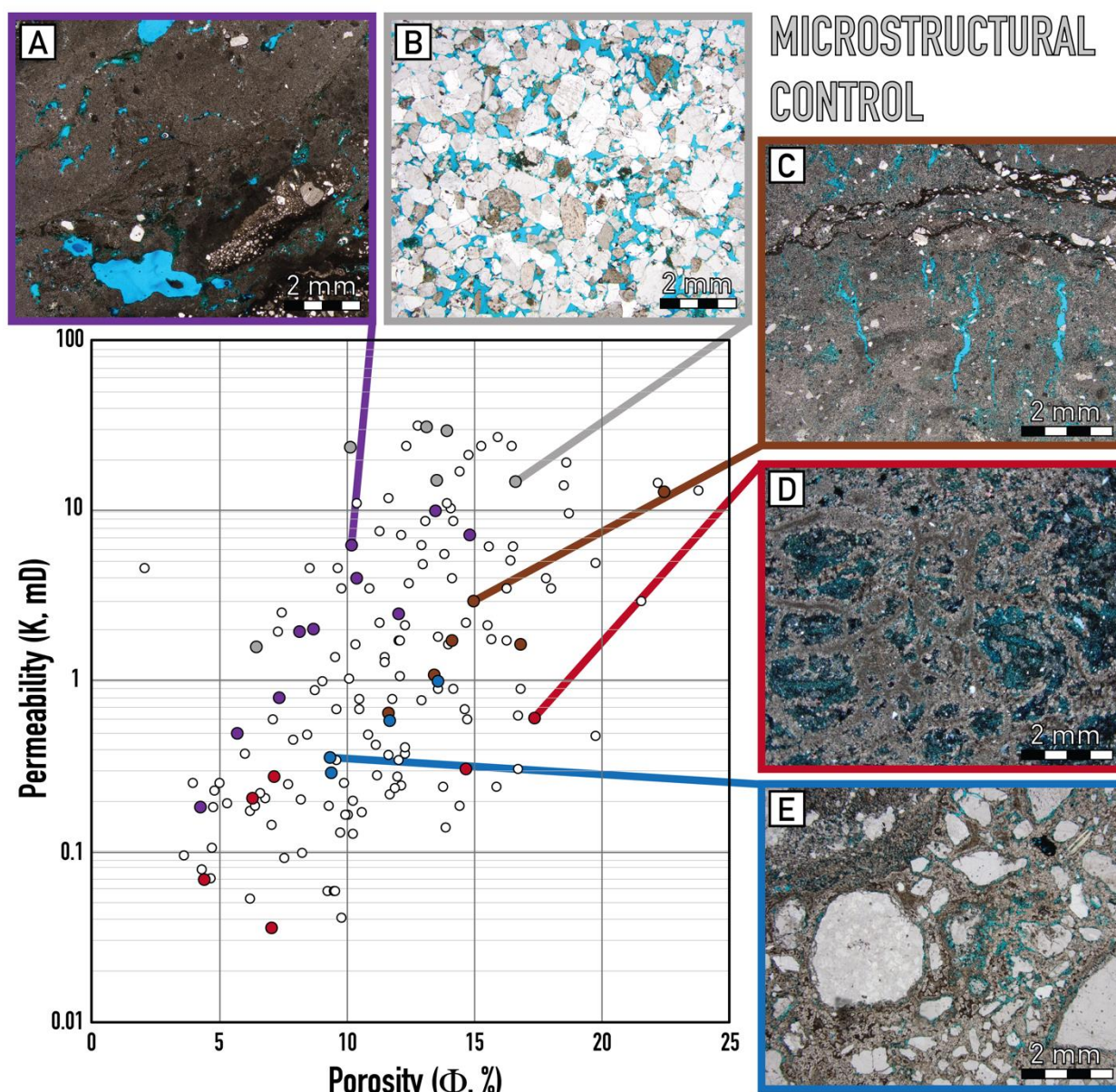
The whole petrophysical dataset is exposed in Figure 26, showing three groups of data corresponding to the type of dataset. Porosity measurements fluctuate between 1 % and 24 % while permeability values fluctuate between 0.01 mD and more than 3 D. We notice differences between the three datasets that may be due to diverse reasons (heterogeneity of samples, measurements conditions...). Indeed, the GEC data presents higher porosity value for the helium measurements, suggesting an overestimation of porosity for these data, while water porosity data of the GEC fits with dataset of VET. In the meanwhile, the maximum permeability of the GEC dataset is equal to 30 mD while the maximum permeability of the VET dataset is two orders of magnitude higher. Given the microstructural heterogeneity of samples due to both sedimentology and diagenesis, we claim for a geological control of these distinctions. Nevertheless, we cannot omit the influence of measurement conditions and we may suggest to conduct new permeability analyses of VET samples using the GEC facilities.



**Figure 26: Cross-plot of permeability and porosity data. VET (Vermillion) data is in white while GEC data is subdivided in two groups corresponding to the type of porosity measurement (air in grey and water in blue).**

### 2.3.5 Microstructural control on petrophysical properties

Based on the microstructural characterization, we defined the main microstructure criteria controlling the permeability (K) and porosity ( $\Phi$ ) properties (Figure 27). Following the microtexture classification and the diagenetic overprint, we firstly define 5 main groups for the GEC samples, including vuggy rich dolomites (Figure 27A), clay-free and porous sandstones (Figure 27B), Vuggy and clay-rich dolomites (Figure 27C), Clay-rich dolomites (Figure 27D) and sandstones, and patchy porous dolomites (Figure 27E).

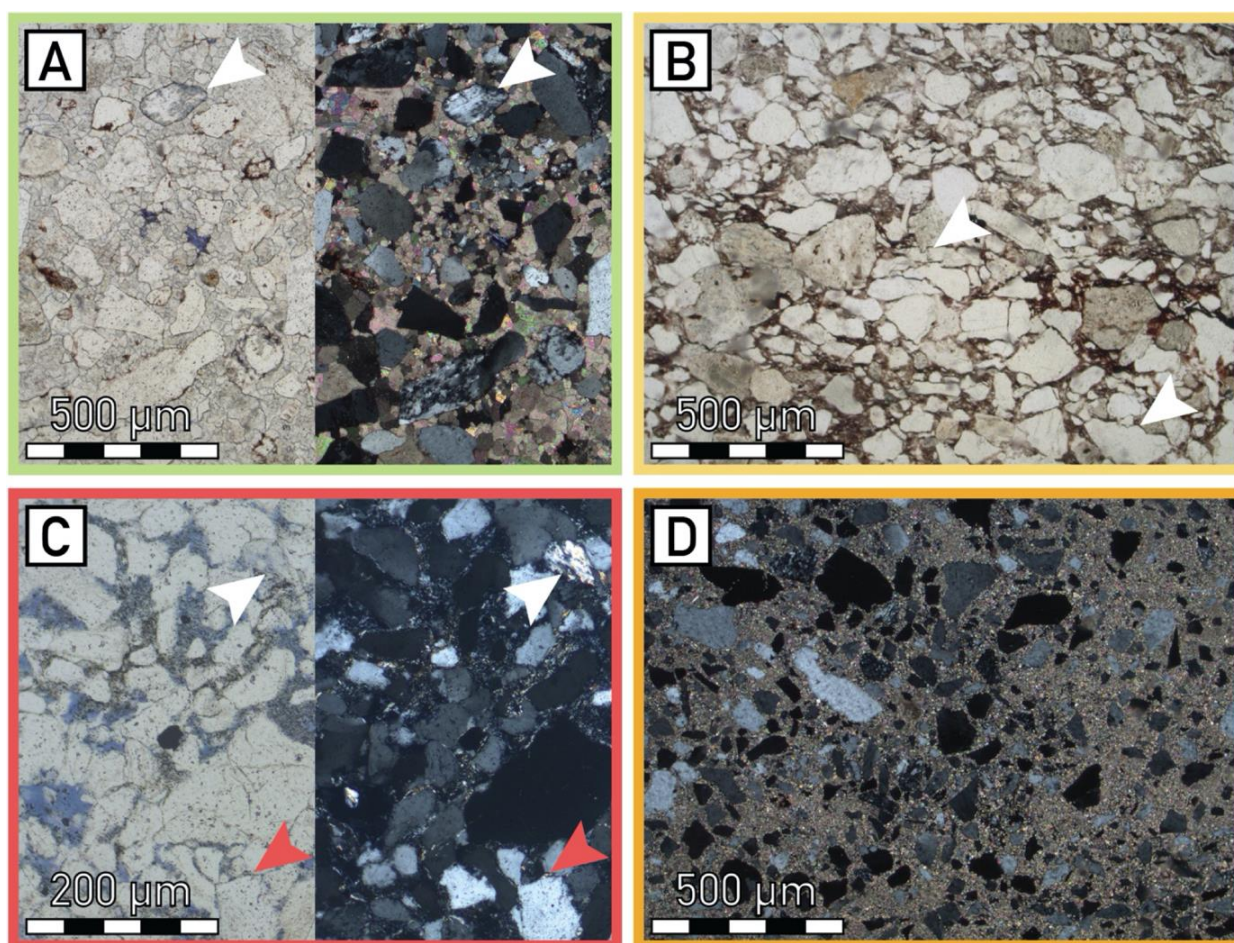


**Figure 27: Microstructural control of porosity and permeability for the samples studied at the GEC.** The dataset is subdivided in five groups, including: (A) Vug-rich dolomite in violet; (B) Porous sandstones highlighting evidences of cement dissolution in grey; (C) Vuggy and clay-rich dolomite in brown, (D) Clay-rich dolomite (and sandstones) in red; (E) Patchy porous dolomites.



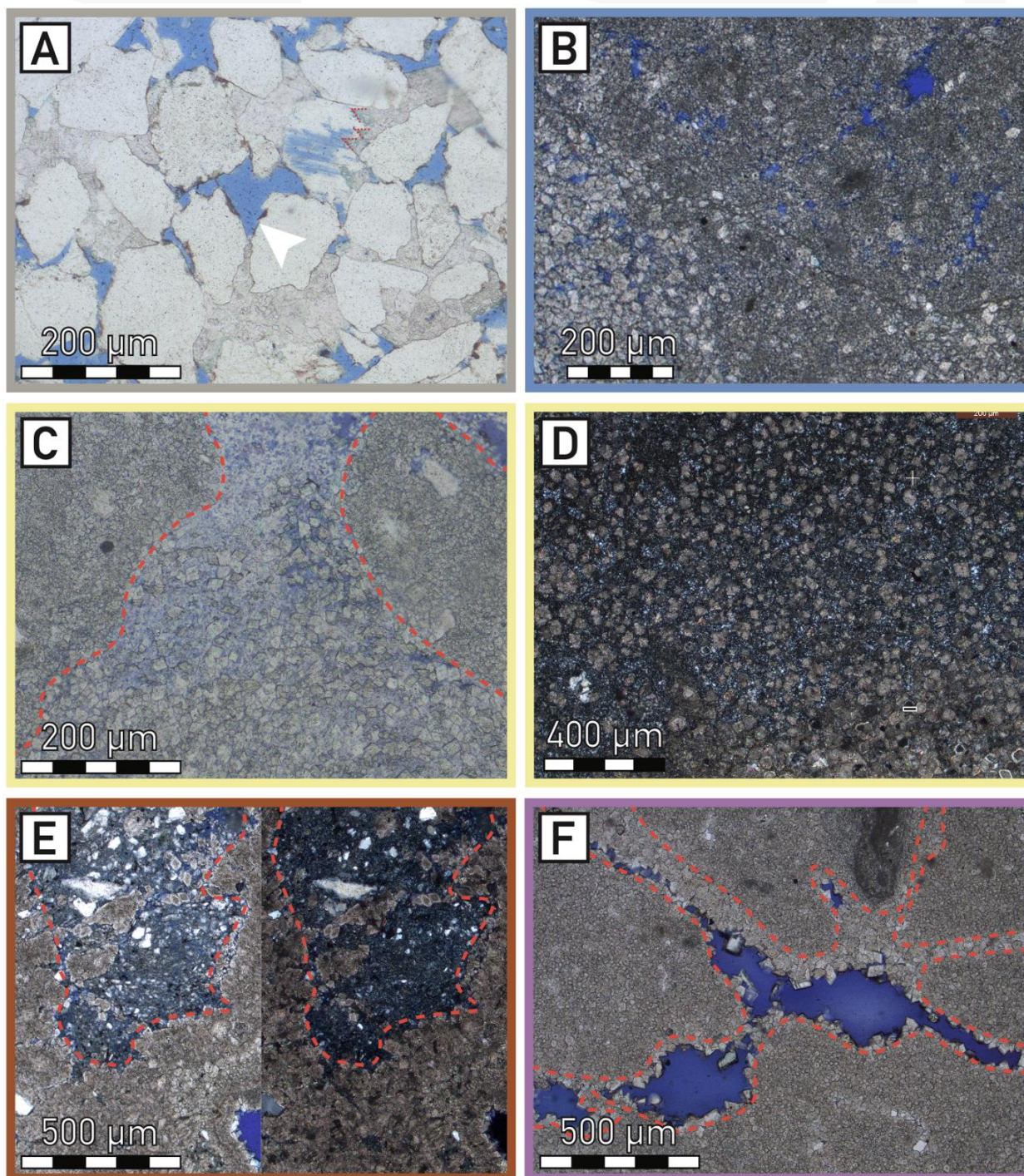
To go further, we distinguish 9 main diagenetic states controlling the porous network:

- i) Carbonate cementation of the intergranular pore space of sandstones (Figure 28A);
- ii) Mechanical compaction of sandstones (Figure 28B),
- iii) Clay coating, clay illuviation and compaction of sandstones (Figure 28C),
- iv) Groundmass dolomitization (Figure 28D),
- v) Dissolution of carbonate cement filling the intergranular pore space of sandstones (Figure 29A),
- vi) Patchy dissolution of groundmass dolomite (Figure 29B),
- vii) Vuggy and patchy dissolution of groundmass dolomite followed by cementation (barite, celestine, silica, Figure 29C) and silica replacement (Figure 29D),
- viii) Vuggy dissolution of groundmass dolomite developed in clays (Figure 29E) and
- ix) Vuggy dissolution of groundmass dolomite remaining empty or followed by pore-lining dolomite cementation (Figure 29F).



**Figure 28: Microscopic views of different diagenetic processes decreasing the reservoir potential, the porosity is in blue: A. Plain polarized light (PPL) and crossed polarized light (XPL) view of a carbonate cement of the intergranular porous network, the white arrows point to a partially leached K-Feldspar. B. PPL view of a clayed sandstone highlighting mechanical compaction, the white arrows point to sutured contacts between quartz grains. C. PPL and XPL views of clay coatings between quartz grains pointed by the red arrows, the white arrows point to a partially leached K-Feldspar. D. XPL view of a groundmass dolomitization between detrital grains.**





**Figure 29: Microscopic views of different diagenetic processes controlling the porous network, the porosity is in blue: A. PPL view of a patchy leached carbonate cement between quartz grains, the white arrow points to this dissolution evidence on a quartz grain showing a relic of an authigenic overgrowth. B. PPL view of a patchy dissolution of the groundmass dolomite. C. PPL view of a vuggy pore affecting a dolomite sample (red dotted line) filled by a dolomite and celestine cement. D. XPL view of microquartz cement partially replacing dolomite crystals. E. PPL and XPL views of a remaining clay-silt matrix partly dolomitized (red dotted line). F. PPL view of a vuggy pore (red dotted line) partially filled by a pore-lining dolomite cement.**

Given the availability of thin-sections of VET and the large amount of petrophysical measurements, we used their dataset to define porosity-permeability trends (Figure 30) based on the diagenetic states previously exposed (Figure 28 & Figure 29). Indeed, these nine diagenetic states allow to explain the huge variations of permeability (K) and porosity ( $\Phi$ ) properties of the studied rocks. Based on the main diagenetic overprint of each sample, we define five main K- $\Phi$  trends, including two trends for sandstone-conglomerate samples and three trends for dolomite samples, summarized as follow (Figure 30):

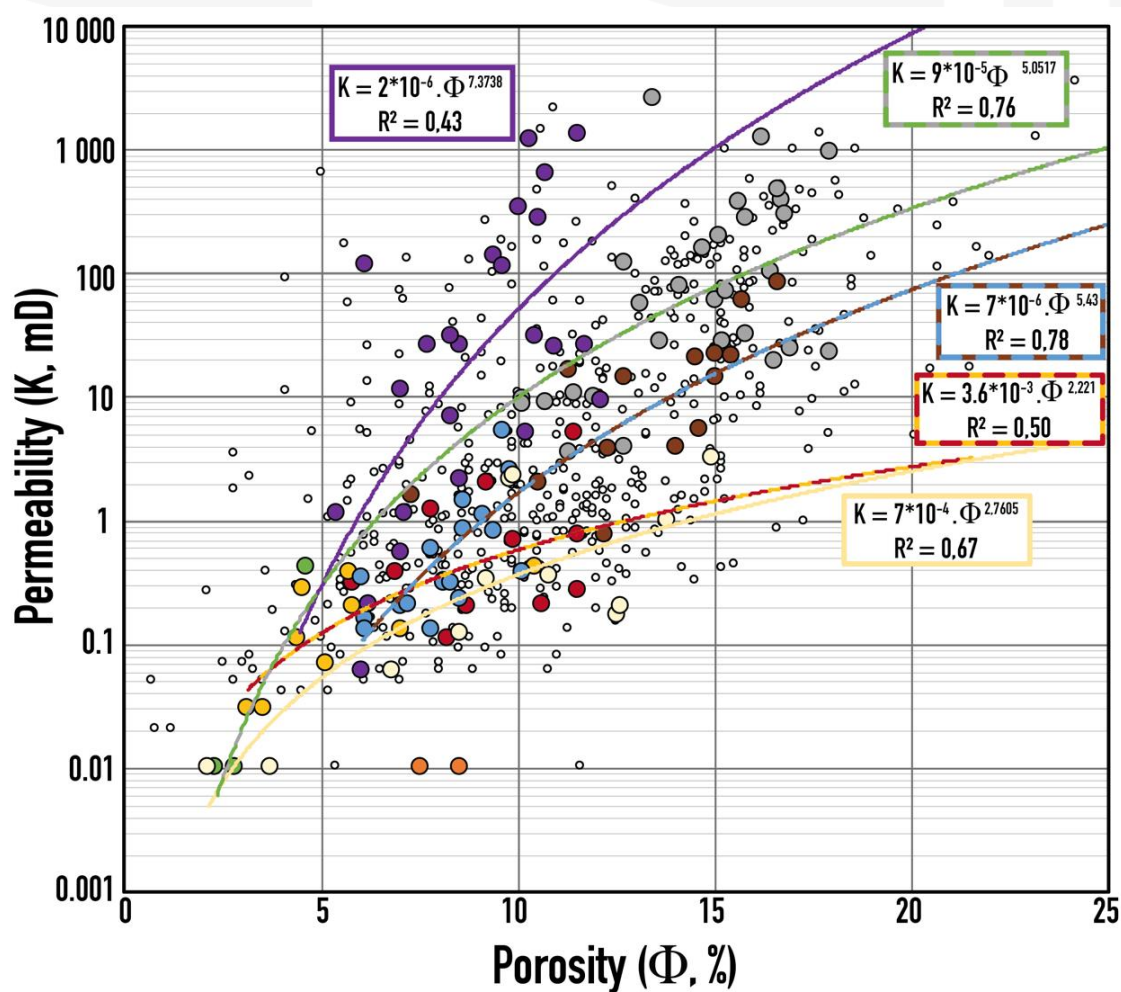
- Mechanical compaction and clay coating/illuviation (dashed red-yellow trend)
- Cementation and dissolution processes (dashed green-grey trend)
- Patchy dissolution of groundmass dolomite together with vuggy dissolution of groundmass dolomite developed in clays (dashed blue-brown trend)
- Dissolution of groundmass dolomite followed by silicification (beige trend)
- Vuggy dissolution of groundmass dolomite followed by pore lining cementation (purple trend)

To go further, we ‘invert’ the available porosity and permeability data of samples not petrographically characterized using the trends defined on Figure 30 together with a check of the lithology based on core pictures, sedimentary logs and available well-log dataset. Such an extrapolation of petrophysical data aims to more precisely define the five main K- $\Phi$  trends while integrating the whole VET petrophysical dataset (Figure 31). Based on this work, we can simplify the diagenetic types controlling the K- $\Phi$  trends and gathering them in 3 classes (Figure 32):

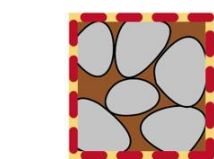
- I. Poor reservoir group including tight dolomites (well-cemented or silicified) and clayed sandstones and conglomerates (compacted and showing evidences of clay coats and illuviation), the red trend;
- II. Moderate reservoir group including patchy dissolved groundmass dolomite together with vuggy dissolved groundmass dolomite developed in clays, the yellow trend;
- III. Good reservoir group gathering the clean sandstones/conglomerates affected by quartz overgrowths and dissolution of a carbonate cement together with the vuggy dolomites, the blue trend.

Such a rock-typing approach based on microstructural criteria (microtexture and diagenetic overprint) aims to understand the wide fluctuations of porosity and permeability. Indeed, the outlined trends display three distinctive petrophysical behaviors explaining the permeability fluctuations. As an example, one order of magnitude separates the permeability prediction of each trend for porosity value higher than 15 % (1 mD for the poor trend, 10 mD for the moderate trend and 100 mD for the good trend, Figure 32).





### Sketches of diagenetic states



Clay coating and illuviation  
+ Mechanical compaction



Carbonate cementation  
of intergranular porosity



Groundmass  
dolomitization (Gr. Dol)



Vuggy dissolution  
of Gr. Dol



Silicification affecting  
dissolved Gr. Dol



Dissolution of  
carbonate cement



Patchy dissolution  
of Gr. Dol



Vuggy dissolution of gr. dol.  
developed within clays

Figure 30: Cross-plot of permeability and porosity dataset studied in this work. The small white dots correspond to samples not petrographically characterized. The colours of other dots correspond to the main diagenetic state petrographically identified, sketched below the cross-plot. The main permeability-porosity trends corresponding to different diagenetic states are also indicated.



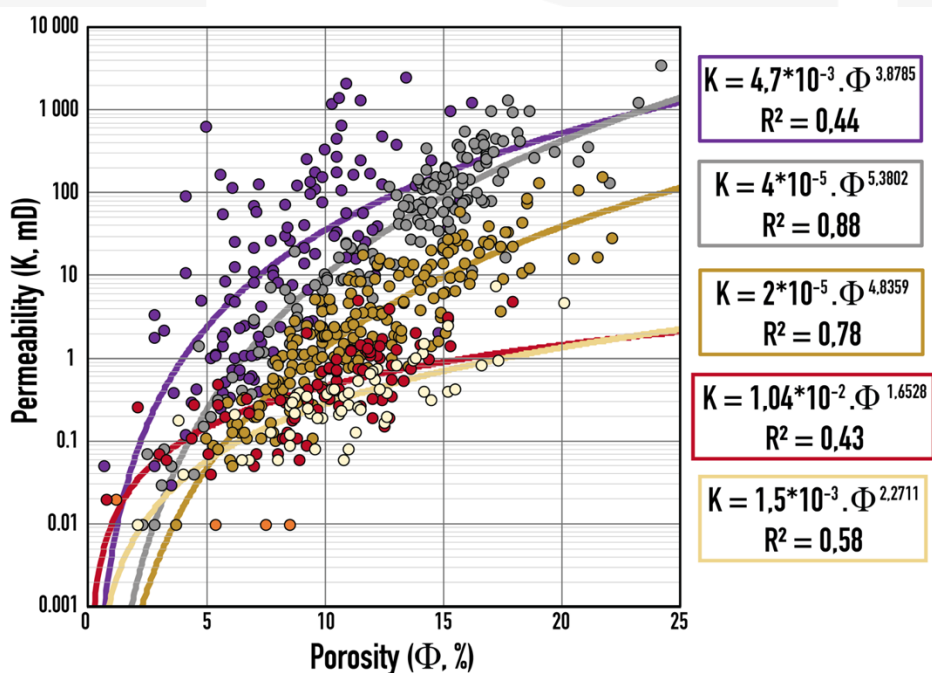


Figure 31: Cross-plot of permeability and porosity data sorted per diagenetic types. The colour code corresponds to the trends defined in Figure 29 (see text for explanations).

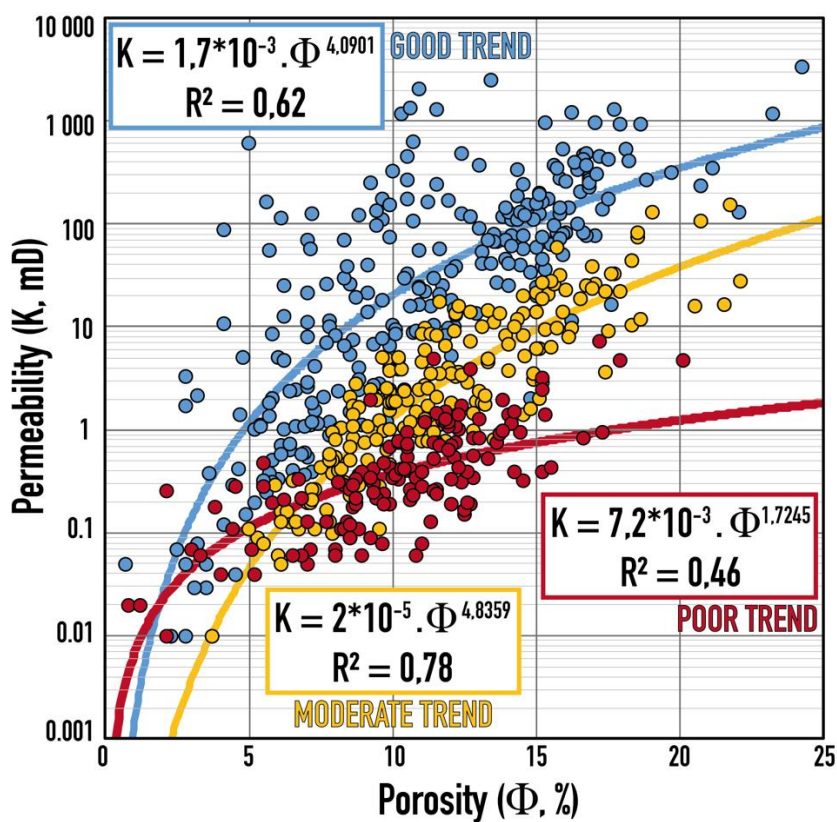


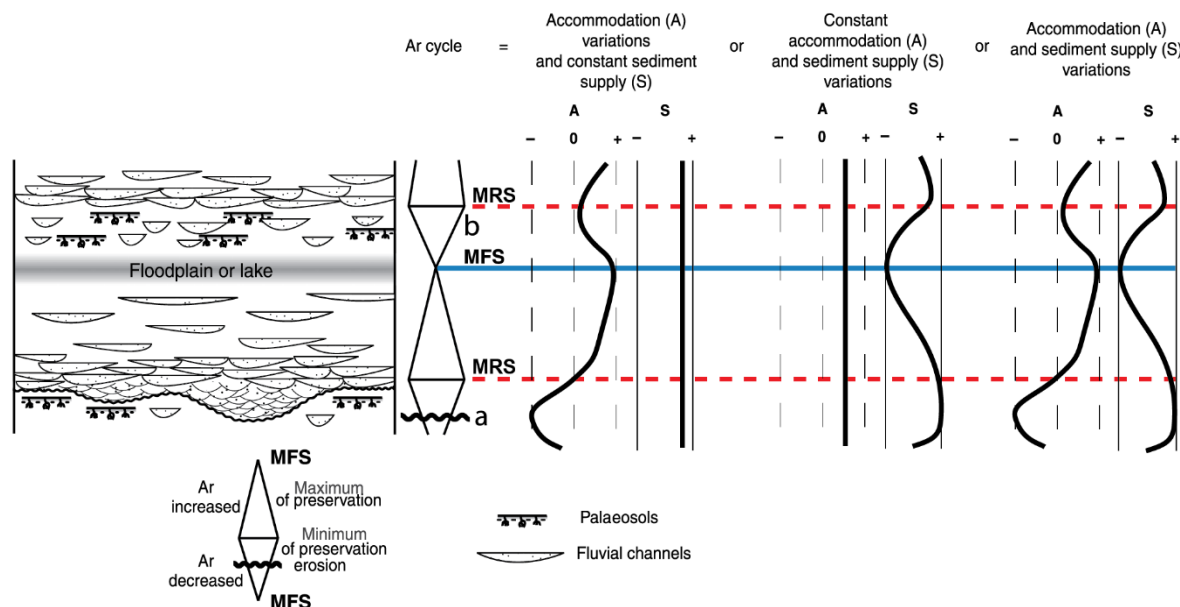
Figure 32: Cross-plot of permeability and porosity data grouped per major rock type.

## 2.4 WELL-LOG ANALYSIS, SEQUENCE STRATIGRAPHY & RESERVOIR MODELING

### 2.4.1 Methodology

In order to depict the sedimentary architecture of the studied reservoir, we apply sequence stratigraphy concepts to distinguish genetic units at the log scale (Figure 33). Such an approach helps to investigate the stratigraphic base-level fluctuations characterized by the accommodation space (A) and sediment supply (S) variations (Wheeler, 1964; Cross, 1988; Galloway, 1989; Bourquin et al., 2009). In continental environments, following Bourquin et al. (2009), the genetic units expose the variation of sediment preservation through two main stages of realized accommodation (Ar):

- A stage of stratigraphic base-level fall marked by a decreasing Ar. It corresponds to an upward-decrease of accommodation and upward-increase of sediment supply, characterized by well-developed paleosoils and erosion surfaces together with amalgamated detrital units, capped by a Maximum Regressive Surface in lake environment (MRS, or turnaround surface) corresponding to a base-level fall to rise transition.
- A stage of stratigraphic base-level rise marked by an increasing Ar. It corresponds to an upward-increase of accommodation and upward-decrease of sediment supply, characterized by well-developed fluvial successions capped by a Maximum Flooding Surface (MFS) corresponding to the maximum maturity of floodplain or lacustrine deposits.



**Figure 33: Definition of genetic units (smallest stratigraphic units) in fluvial and fluvial-lake environment (adapted from Bourquin et al., 2009). Such a unit represents the realized accommodation ( $A_r$ ) induced by variations in accommodation space ( $A$ ) and/or sediment supply ( $S$ ). MFS: Maximum Flooding Surface, MRS Maximum Regressive Surface. Note that depending on the sedimentary environments, the erosion surface may be either preserved (case a) or not recorded (case b).**



In order to predict the genetic unit variations in the ‘uncored’ intervals, we defined their well-log signatures following the methodology of Bourquin et al. (1998) and reconstructed the genetic sequence stacking pattern for the eight studied wells (see Figure 5 for their location, see Annexes). For this purpose, we use several well-log tools, including the Caliper, Gamma Ray, CGR and SGR Gamma Ray, U/Th/K content, Photoelectric factor, Neutron porosity, Density and Sonic. On the logs, 0% of neutron porosity (NPhi) is equal to 2.70 g.cm<sup>3</sup> of density (RhoB). NPhi is increasing to the left while RhoB is increasing to the right. Then, we established correlation between the wells based on the main stratigraphic surfaces recognized in all wells (MFS used as time markers). Finally, we integrated the rock types within the stratigraphic framework.

### 2.4.2 Electrofacies definition

Following the work of Bourquin et al. (1998), we defined seven main electrofacies (Table 3) based on the integration of well-log dataset and geological descriptions of four wells, including wells B, C, E & H (see Figure 5 for location). This classification is based on:

- The polarity, depending on the NPhi-RhoB variations, which is negative when the porosity curve is on the right of the density curve (yellow colour) and positive when the porosity curve is on the left of the density curve (green colour) and the spacing between these two curves;
- The Gamma-Ray reflecting the natural radioactivity of the rocks, aiming to detect clays or feldspathic sandstones,
- The RHG deviation (Raymer Hunt Gardner Deviation, adapted from Raymer et al., 1980 and Anselmetti & Eberli, 1999). It is based on the computation of a theoretical velocity:  $V_{pRHG} = (1 - NPhi)^2 * V_{pDolomite} + NPhi * V_{pWater}$ , (Raymer et al., 1980,  $V_{pDolomite} = 7349 \text{ m.s}^{-1}$ ;  $V_{pWater} = 1500 \text{ m.s}^{-1}$ ) and the comparison of this value with the real velocity given by Sonic,
- NPhi, giving a first idea on the porosity of the studied rocks,
- RhoB, informing on the density of the studied rocks,
- The Photoelectric factor (PEF, barn per electron – b/e), sensitive to the presence of heavy atoms contained in sulphates and sulphides.

The Figure 34 presents the integration of well-log data, sedimentary logging, depositional environment evolution and rock types layering based on petrophysical measurements for the well B. Electrofacies were defined as follow:

- Electrofacies I and II gather several braided alluvial fan depositional environments, including channels, debris flow, fan delta and lag deposits. Electrofacies III includes heterolytic sandstones and conglomerates and immature dolomitized (not recognizable as dolomites using the well-log tools) sandstones and conglomerates that characterize a fluctuating environment showing alternation between channel and overbank deposits.

**Table 3: Electrofacies classification based on well-log data and lithofacies description. The description scale of each column is as follow: RhoB-NPhi spreading: <0.05 very low / 0.05-0.1 low / 0.1-0.2 medium / >0.2 high; Gamma Ray (api): <60 low / 60-90 medium / >90 High; RHG deviation (m.s<sup>-1</sup>): <500 low / 500-1000 medium / 1000-1500 high / >1500 very high; NPhi (%): <0.05 very low / 0.05-0.1 low / 0.1-0.15 medium / 0.15-0.2 high / >0.2 very high; RhoB (g/cm<sup>3</sup>): <2.4 very low / 2.4-2.5 low / 2.5-2.6 medium/ 2.6-2.7 high / >2.7 very high; PEF (b/e): <2.5 low / 2.5-3 medium/ 3-3.5 high / >3.5 very high.**

Electrofacies	Polarity & RhoB-Nphi spreading	Gamma Ray	RHG deviation	Nphi	RhoB	PEF	Corresponding facies	Depositional environment
<b>I</b>	Negative Low to medium	Low to high	Negative Mostly medium to very high	Mostly low to medium occurrences of high	Very low to medium	Low to medium	<b><i>Conglomerate facies</i></b> - Gh, Gm, Gmu, Gp, Gt, Gtp <b><i>Sandstone facies</i></b> - S, Sb, Sh, Shb, Sm, Sp, St, Stp	<b><i>Channels, Debris flow and Fan delta deposits</i></b>
<b>II</b>	Negative to positive Very low to low	Low to medium	Negative Medium to very high	Mostly medium	Low to medium	Low to medium	<b><i>Conglomerate facies</i></b> - Gm, Gi, Gh	<b><i>Lag deposits</i></b>
<b>III</b>	Positive to negative Very low to medium	Medium to high		Very low to medium	Low to medium	Low to medium	<b><i>Heterolitic Conglomerate and Sandstone facies</i></b> - Gm, Gmu, Gp, Sb, Shb, Sm, St, SF, SFb <b><i>Immature Dolomitized Sandstone &amp; Conglomerate facies</i></b> - GD, Gmu-D, SD, SbD, Sh-D	<b><i>Alternation between Channels and Overbank deposits</i></b>  <b><i>Dolomitized sandstones &amp; conglomerates</i></b>
<b>IV</b>	Positive Medium to high	Medium to high	Negative Mostly medium to high	Medium to very high	Low to medium	Low to high	<b><i>Clay facies</i></b> - F, Fl, Flb	<b><i>Alluvial floodplain or lake</i></b>
<b>V</b>	Positive Low to very low	Medium to high	Negative Mostly medium to high	Medium to high	Low to medium	Low to medium	<b><i>Heterolitic clay facies</i></b> - SF, SFb facies and alternation of F, St, Sh, Shb, Sm, Gmu	<b><i>Overbank deposits in floodplain or lakes</i></b>
<b>VI</b>	Positive Mostly high (highest spreading)	Mostly low	Positive and negative Mostly low	High to very high	Medium to very high	Mostly high to very high	<b><i>Massive dolomitic facies</i></b> - DF, Dn, Dh	<b><i>Paleosoils, dolocrust possibly karstified</i></b>  <b><i>Dolomitized sandstones &amp; conglomerates</i></b>
<b>VII</b>	Positive Mostly medium	Low to high	Negative Medium to high, sometimes low	Medium to very high	Medium to very high	Mostly high to very high	<b><i>Nodular dolomitic facies and dolomitic facies with clays-Dh, Dn</i></b> <b><i>Immature Dolomitized Sandstone &amp; Conglomerate facies</i></b> - GD, Gmu-D, SD, SbD, Sh-D	

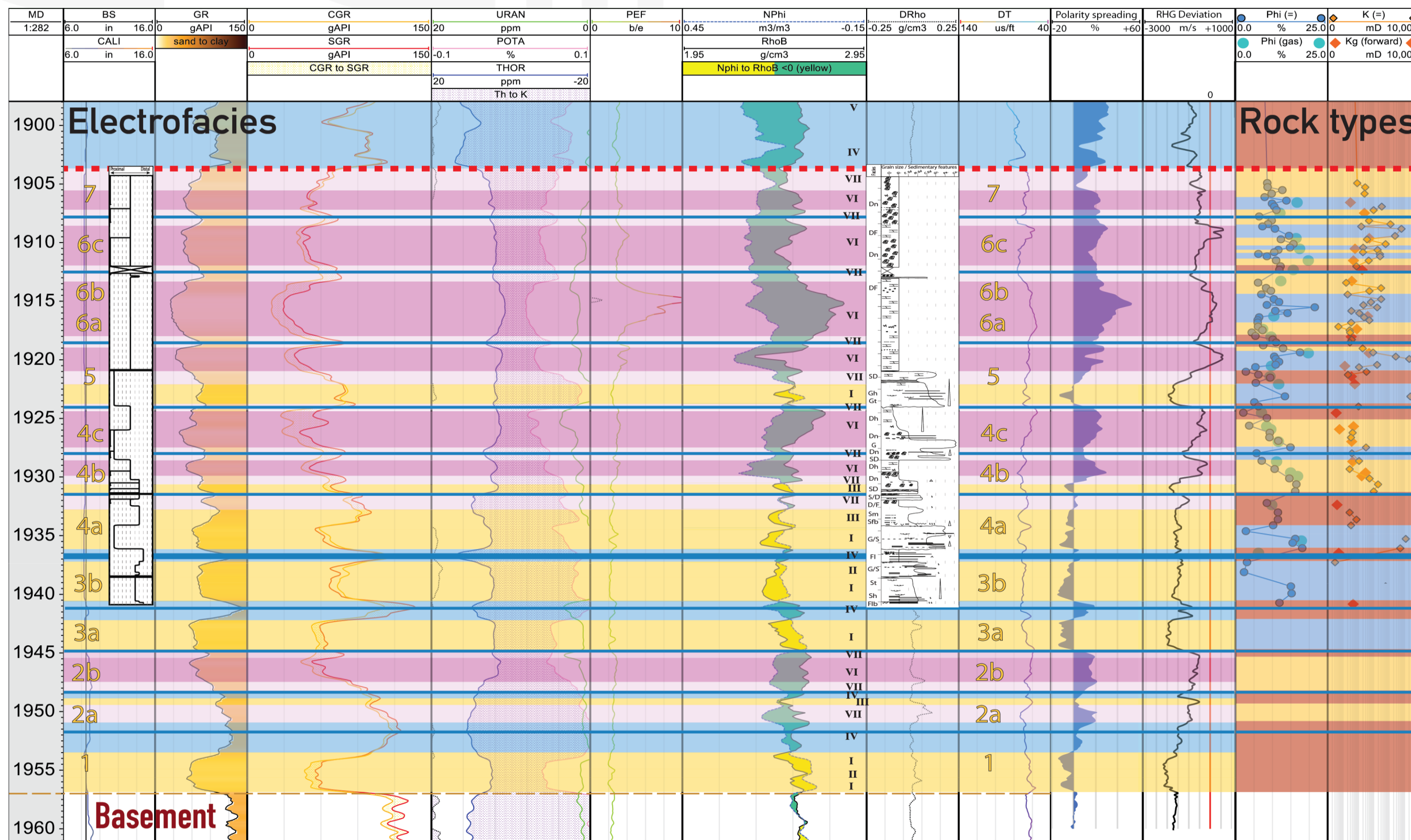


- Electrofacies IV and V gather the clay and heterolithic clay facies corresponding to alluvial floodplain or lakes with occurrences of overbank.
- Finally, Electrofacies VI and VII correspond to the dolomite facies. The electrofacies VI is only related to poorly radioactive massive dolomites (facies Dn and Dh and a few occurrence of DF), while the electrofacies VII includes moderately to highly radioactive dolomites together with dolomitized sandstones and conglomerates.

As showed by the Figure 34, the vertical stacking of depositional environments is highlighted by the evolution of electrofacies. Based on the depositional model defined earlier (Figure 10), we delimit key markers that correspond to high resolution MFS. Usually, these MFS matches with the most distal environments including floodplain and lacustrine deposits, so electrofacies IV and V (markers at the top of units 1, 2a, 3a and 3b). However, the high occurrences of clay-rich dolomites allow us to recognize additional markers that match with paleosol development on previous floodplain and lacustrine deposits (facies FDn, D) and clay infill of vuggy dolomites (facies DF), so electrofacies VII (markers at the top of units 2b, 4a, 4b, 4c, 5, 6b, 6c and 7). Such key markers will be used for correlation purposes.

Furthermore, the previously determined rock types (Figure 32) are confronted to the depositional environment evolution on the Figure 34. You may notice that the most part of the units associated with MFS defined using genetic stratigraphy principles are corresponding to the poor reservoir group (top of units 1, 2a, 2b, 3a, 3b, 4a, 4c, 5, 6b and 7, red rock type). However, two markers point to moderate and good reservoir trends (top of units 4b and 6c, yellow and blue rock type) which is obviously explained by the wide heterogeneities of the microstructure due to diagenetic overprint. Indeed, these markers are associated with the electrofacies VII that gather clay-rich dolomites and dolomitized sandstones that may present local vuggy pores and dissolved cements.

All in all, the integration of both depositional environment evolution and rock typing allow us to characterize the reservoir properties with a high resolution (meter-scale). Such an approach is essential if one wants to understand the hydraulic behaviour of heterogeneous sedimentary formations such as the studied Triassic sandstones and dolomites.



**Figure 34: Electrofacies and rock type classification defined for the well B (see Figure 5 for location of the well). This figure gathers the sedimentary log, depositional environment evolution, main stratigraphic surfaces (MFS: blue lines, MRS: red line), well-log data and petrophysical data used for classification, with from the left to the right: Caliper (CALI), Gamma Ray (GR), CGR and SGR Gamma Ray, U/Th/K content, Photoelectric factor (PEF), Neutron porosity (NPhi), Density (RhoB), Sonic (DT), Polarity spreading (normalized scale), RHG deviation, and Porosity (Phi) / Permeability (K) of plugs**



### 2.4.3 Stratigraphic correlation and integration of rock types

The closely spaced configuration of wells (about 1 km between each well, except for A-B distance, Figure 5), allow us to establish a well-defined stratigraphic correlation (Figure 35). Such a figure aims to depict the spatial evolution of depositional environment and highlights two major series at the reservoir scale:

- The first series includes five high-resolution meter-scale units (1, 2a, 2b, 3a, 3b). It directly overlies the basement and is capped by a meter-scale heterolytic clay interval corresponding to a major MFS (labelled ‘minor cycle MFS’, Figure 35). Looking more into details, we can define 4 high resolution MFS, Figure 35. We note that one of these MFS (top of unit 3a) is not continuous and only suspected in wells C and H. The four high resolution MFS delineate five units mainly composed of conglomerates/sandstones (EF I, II and III) and clays (EF IV and V) deposits in braided alluvial fan and floodplain environment. These units may evolve laterally into dolomites in units 2a and 2b, which are peculiarly well-expressed in wells B, C and D, suggesting a local dolomitization associated with soil development.
- The second series includes eight high-resolution units (4a, 4b, 4c, 5, 6a, 6b, 6c and 7). It overlies the major MFS and is capped by a maximum regressive surface (MRS, Figure 35). This second series is subdivided thanks to seven high resolution MFS (labelled ‘minor cycle MFS’, Figure 35). Two of these MFS (top of units 6a and 6b) are only expected in wells C, F, G and H. The eight subdivided units are mainly composed of sandstones and conglomerates characterizing (EF I, II and III) a braided alluvial fan that is highly affected by dolomitization and pedogenic overprint (EF VI and VII). Moreover, the Figure 35 highlights a significant lateral variation of depositional environment as showed by the interdigitation of sandstones/conglomerates (EF I, II and III) within the dolomites (EF VI and VII), peculiarly well-expressed in the units 5, 6a, 6b and 6c. These lateral variations are common in continental environments. Here, they suggest the occurrence of geographical high points allowing the development of paleosols and dolomitization (wells A, B, D, F and H) possibly separated by areas of transit by-pass associated with sandstones and conglomerates deposition (wells C, E and G). According to Figure 35, the second series is capped by a pure dolomite unit topped by a major transgressive surface.

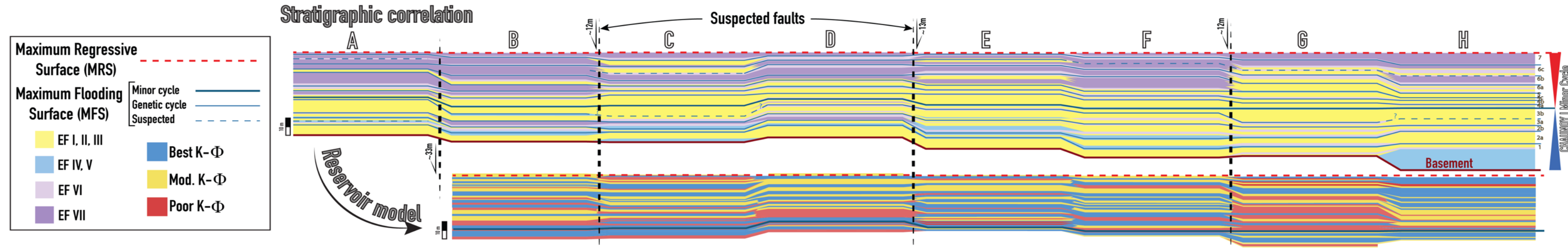


Figure 35: Stratigraphic correlation and resulting reservoir model based on genetic stratigraphy principles and rock type definition.



These two main series match with a minor cycle (major base level rise and fall) that corresponds to the Chaunoy I minor cycle of Bourquin et al. (1998). Based on the depth's variation of the major transgressive surface (see Annexes), we suggest the occurrence of four normal faults that may induce decameter-scale shifting (12, 13 and 33 meter shifts). Such a structural overprint may influence the large-scale compartmentalization of the reservoir. Given the proposed shifts, these theoretical faults affected the Triassic after its deposition (knowing that several extension and compression phases occur during opening and closing of the Tethys in the Paris basin). Nevertheless, we cannot reject the hypothesis of local syn-sedimentary faulting that may potentially have influenced the Upper Triassic deposition.

Finally, in order to accurately understand the heterogeneities of the petrophysical properties, we integrated the three rock types defined in Figure 32 within the stratigraphic framework (Figure 35). Such a correlation allows to highlight a wide variation of the porosity-permeability trends at the scale of the reservoir. According to discussions with C. Raddadi (Vermilion Emeraude), this reservoir presents a very good lateral and vertical hydraulic connectivity. While the lateral connectivity is well-understood thanks to our reservoir model that shows a large extension of the best and moderate K- $\Phi$  units (respectively blue and yellow areas in Figure 35), we are facing an issue for the vertical connectivity. However, this vertical connectivity may be explained by two reasons: i) a very low proportion of poor K- $\Phi$  units that are not constant laterally (red areas in Figure 35) and ii) the hypothetical occurrences of faults (vertical dashed lines in Figure 35).

All in all, our conceptual reservoir model integrates both i) the sedimentary architecture controlled by depositional environment evolution and ii) the high-resolution variation of petrophysical properties controlled by the microstructure evolution that consider sedimentological microtextures and diagenetic overprint. The multi-scale and integrative approach presented here is essential if one wants to understand the hydraulic behaviour of heterogeneous sedimentary formations such as the presently investigated Triassic sandstones and dolomites.

#### 2.4.4 3D reservoir modeling

The very large amount of data CYU had accessed to, on which this study is based, required a full integration in a 3D modeller (Petrel®) for ease of reading. In this way, all the available data, but also any new dataset acquired in the laboratory such as petrophysical measurements and position of thin-sections as well as many others, made it possible to standardise the interpretative documents (Figure 35 and Annexe 3 for example). Figure 34 illustrates the diversity of data collected in each well (See Annexe 2 for details on every single well) and by extension in this 3D model. Moreover, modelling was essential in order to locate the wells in depth, since the majority of the wells are deviated (Figure 36) and many documents refer to the measured depth, which can lead to confusion in the identification of key horizons between wells. Well-log data were thus converted to True Vertical Depth from Sea Level (SSTVD) for uniformity. The figures also highlight the top Triassic marker (purple) and top basement marker (brown). All the work

performed for reservoir characterization is concentrated between these two markers. Gamma-Ray and core sections, as well as electrofacies defined in Table 3 (part 2.4.3) are represented in Figure 37 and Figure 38.

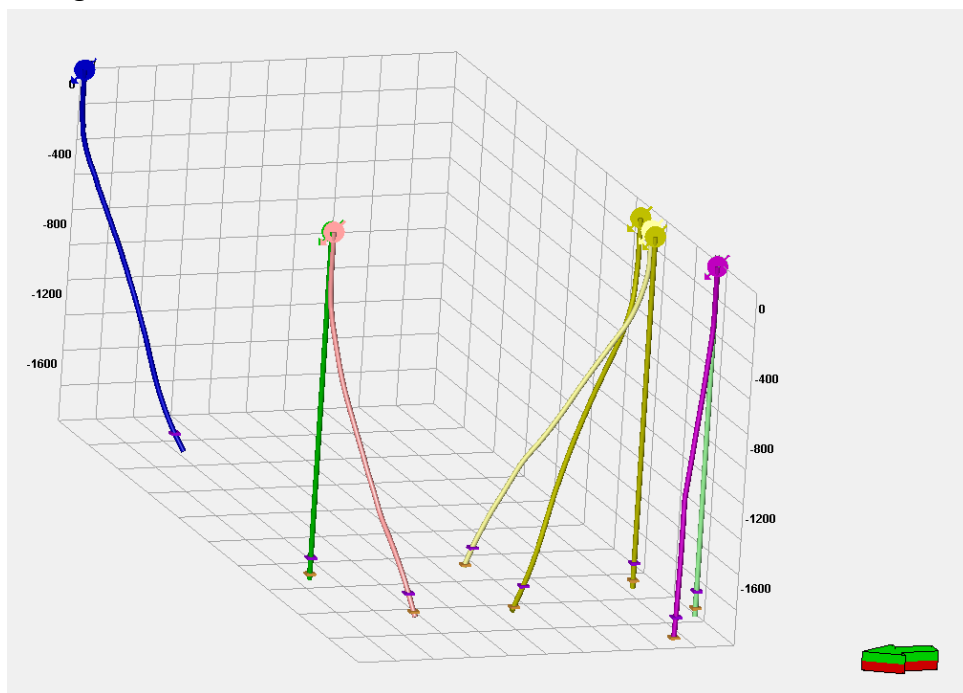


Figure 36: 3D view of Vert-le-Grand field (at scale). Refer to Fig. 2-5 to identify borehole A to H. The purple marker corresponds to the top Triassic while the brown marker highlights the top basement.

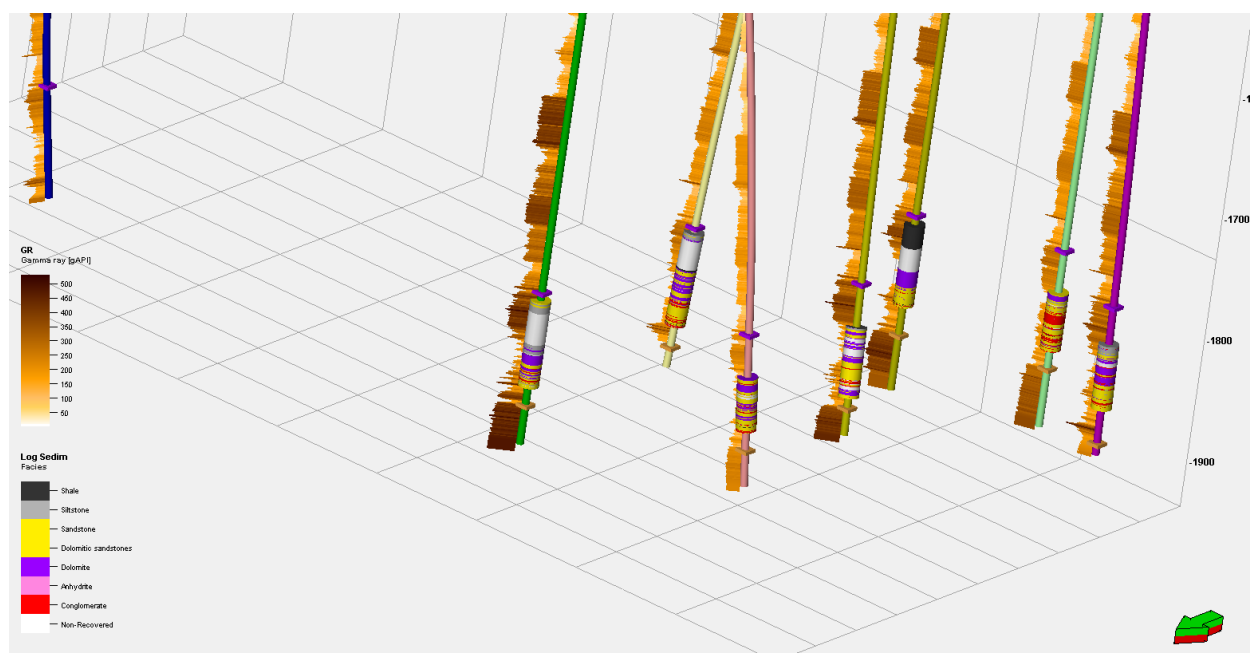
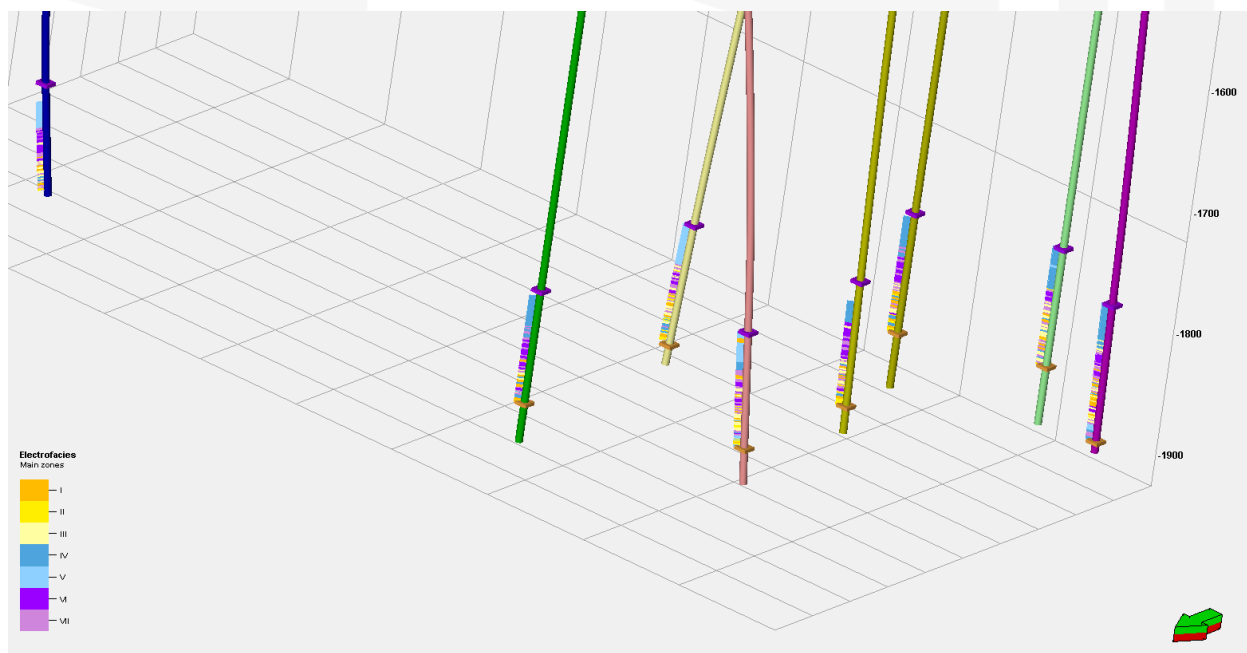


Figure 37: Gamma Ray and cored sections studied for sedimentary characterization (vertical scale exaggerated x5).



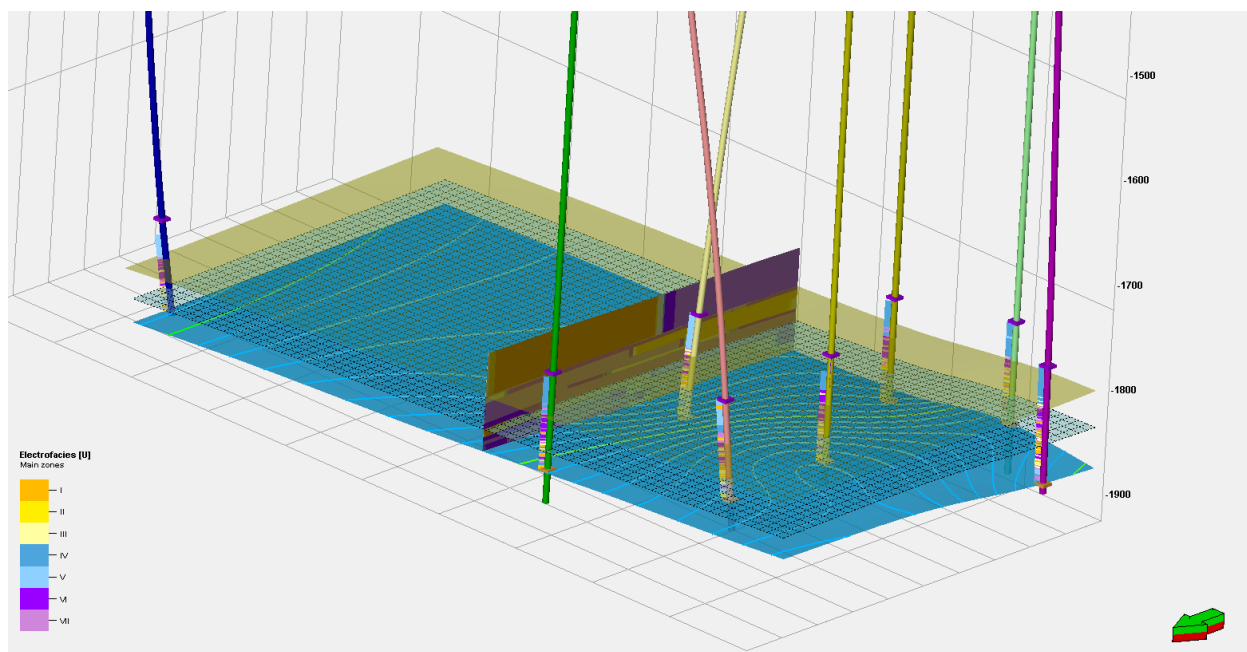


**Figure 38: Electrofacies defined in Table 3 (part 2.4.3) and extrapolated for the entire Triassic section on each well (vertical scale exaggerated x5).**

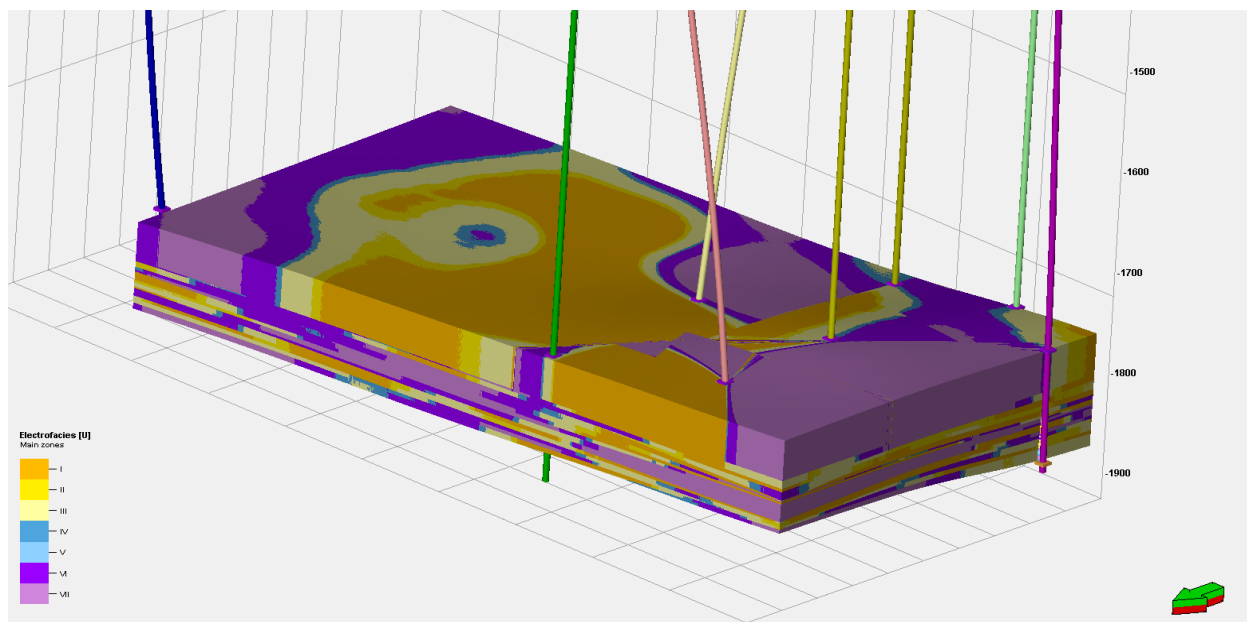
As the interpretations of high-resolution sequence stratigraphy allowed to define the MFS at well scale, Petrel® enabled to extrapolate these reference markers to the entire subsurface area and to deduce the corresponding 3D surfaces. All these surfaces were calculated but for simplification purposes, only the main surfaces were represented (Figure 39), i.e. the base surface, the top of sequence 3b that marks the top of the first high-resolution series (main MFS), and the top of sequence 7 that marks the top of the second high-resolution series (MRS).

In order to better characterize the horizontal and vertical heterogeneity of the Chaunoy sandstones and Vert-le-Grand dolomites reservoirs, a property modelling was performed. The creation of the 3D grid took into account the eleven high-resolution MFS that separate the genetic sequences. The electrofacies interpreted for each individual well were extrapolated to this grid according to a truncated Gaussian simulation in order to populate the 3D model. This basic geostatistical approach was carried out in the purpose of a first attempt to create a static model that could serve as a basis for further investigation. However, neither the probability of finding specific facies along directional trends nor the horizontal/vertical random sampling of potential facies could be defined before running the property modelling. At a first sight, one can remark that the horizontal succession of facies is the same than the order of main zones of electrofacies qualified in the software. There is clearly a bias in the way the grid is populated through. In addition, the high precision of the electrofacies at the well-scale could not be reproduced in the 3D space, which is not satisfying since we want to predict the heterogeneities based on the high-quality interpretations of well-logs and cores. To go further, it would be interesting to test other kinds of grids (structured or unstructured, equivolumic or heterovolumic, etc.) but also, and more importantly, to integrate petrophysical properties as well

as microstructural controlling factors allowing to assess whether the quality of certain layers of the reservoir are poor, fair or good, as it was established in the present report. This experiment is a first step for creating a robust 3D static model of this reservoir. Hence, this work is under progress and will potentially bring new results in the near future.



**Figure 39: Representation of the three main key surfaces from sequence stratigraphy analysis (vertical scale exaggerated x5). The isohypses of the top basement are also indicated. The N-S cross-section corresponds to the simulation obtained from 3D property modelling of electrofacies.**



**Figure 40: Preliminary 3D property modelling of electrofacies based on truncated Gaussian simulation of individual wells, taking into account the eleven high-resolution MFS for the creation of the 3D grid (vertical scale exaggerated x5).**



## 2.5 CONCLUSION & PERSPECTIVES

In this deliverable, we propose an integrative workflow allowing to i) precisely characterize the multi-scale geological heterogeneities of a Triassic reservoir from the Paris Basin, and ii) their controls on the spatial distribution of petrophysical properties. Following the conceptual scales of Haldorsen & Lake (1983), we can summarize the main conclusions of our work as follow (Figure 41):

- At microscopic scale (namely the pore scale, millimeter scale), we faced a huge variability of the microstructure in terms of mineral content (dolomite, quartz, feldspar, clays...) and porous network (uniform intergranular or patchy intercrystalline porosity, microporosity, vuggy porosity...). We showed that this variability is resulting from the combination of 6 main microtextures that may be overprinted by (at least) 18 diagenetic processes. Combining petrographic characterization and petrophysical measurements of porosity and permeability, we showed that the fluid-flow behaviour is controlled by 9 main diagenetic states that can be merged into 3 major rock types. The definition of these rock types allowed us to clearly outline 3 distinct porosity-permeability trends that depend on well-defined microstructural criteria.
- At macroscopic scale (namely the lithofacies scale, centimeter scale to meter scale), based on the description of cores, we distinguished 23 lithofacies that are classified depending on their lithologies (conglomerates, sandstones, dolomite and clays) and structures (*e.g.* cross-bedding, bioturbation, matrix- or clast-supported, presence of nodules, ...). Such a classification allowed us to depict the depositional (*e.g.* low *versus* high hydrodynamic conditions, ...) and diagenetic (pedogenic dolomitization, phreatic dolomitization) processes that controlled the accumulation of the studied sedimentary rocks.
- At mesoscopic scale (namely the size of model gridblocks related to the facies association, meter to decimeter scale), based on sedimentary logging, we interpret the vertical lithofacies variation in terms of depositional environment evolution. This step allows us to precisely define about 23 of facies that were grouped into 7 main environments (paleosoils, braided alluvial fan channels and overbank, floodplain, lake...). Such a work allowed us to define a sedimentary model that was suitable to state the stratigraphic evolution of the studied deposits. Based on genetic stratigraphy, we highlighted several key surfaces (corresponding to Maximum Flooding Surfaces – MFS).
- At gigascopic scale (namely the formation scale, related to genetic stratigraphy), we combined the facies association definition together with the classification of seven electrofacies using an extensive well-log dataset (gamma ray, neutron porosity, density, sonic...). This step was essential for our study as it allowed us to interpret the spatial evolution of depositional environment solely based on well-log data. Using genetic

stratigraphy principles, we defined 13 key surfaces (MFS) that were used for i) well-to-well correlation and ii) development of a high resolution 2-D transect.

- Finally, we integrate the previously defined rock-types within the highly-resolution stratigraphic transect in order to depict the reservoir compartmentalization. For this step, we use our multi-scale characterization that includes i) the microstructural control of petrophysical properties (microscopic scale) and ii) the spatial evolution of petrophysical properties based on the well-constrained sedimentary architecture (gathering macroscopic, megascopic and gigascopic heterogeneities). Our model suggests a very good lateral hydraulic connectivity. It can be used for defining key flow units and local permeability barriers.

To go further, we started to build a static model of the studied Triassic reservoir which is based on the integration of key surfaces (MFS) together with the electrofacies evolution. Yet for now, we have not integrated the microstructural control of petrophysical properties within the model. However, this step is crucial for the development of a geologically well-constrained static model that may serve to simulate fluid-flow and heat transfer in the future. Given that such a goal is beyond our deliverable tasks, a researcher from the GEC lab submitted a research project aiming to tackle these important issues for geothermal development within sedimentary basins (application not related to the MEET project). His proposal is subdivided into two main research axes that propose to i) build high resolution 3D static models using geostatistics based on data from this study and to ii) use dynamic modeling based on realistic geological models in order to understand and predict the geothermal behavior of the studied heterogeneous reservoir. Several simulation scenarios can be tested depending on the uncertainties concerning the geology of the studied aquifer (occurrence of faults between the wells, lateral continuity of permeable/impermeable layers...). However, such simulations will need to be compared with existing production data if we want to build an accurate and realistic dynamic model. This research project may provide a global concept on geology-based modelling, using a comprehensive and integrative workflow. It may help us to reduce the uncertainties of geothermal energy management within heterogeneous sedimentary aquifers (*e.g.* understanding of the hydraulic connectivity and quantification of thermal dispersion). Results from this research project may likely be used as an example to grasp the geological risks in order to ensure an efficient and safe exploitation of geothermal energy within sedimentary basins.

Considering perspectives for geothermal exploration within the Triassic from the Paris Basin, one can consider to monitor cross-well seismic in order to characterize the geological heterogeneities with a resolution higher than surface seismic. Indeed, cross-well seismic allows to depict high-resolution seismic reflectors corresponding to meter-scale impedance contrasts that may mimic the sedimentary architecture in terms of lithofacies and diagenesis (see Bailly et al., 2019b for an example in carbonates). The obtained seismic profiles may be interpreted in the light of sequence



stratigraphy and can serve to build geologically well-constrained reservoir model with a high-resolution by combining seismic inversion and rock typing (e.g. Parra et al., 2003), aiming to characterizing the lateral variation of sedimentary bodies. Furthermore, knowing that the application of full waveform inversion (FWI) on cross-well seismic data (Barnes et al., 2008) can allow characterizing small-scale faults (Takougang et al., 2019), FWI may be used for better characterizing the reservoir compartmentalization in regard to structural features. These purposes are in line with the recommendations of Bugarel et al. (2018) concerning the optimum and sustainable exploitation of geothermal energy within siliciclastic reservoirs and may complete the large spectrum of scales investigated in the present report (Figure 41).

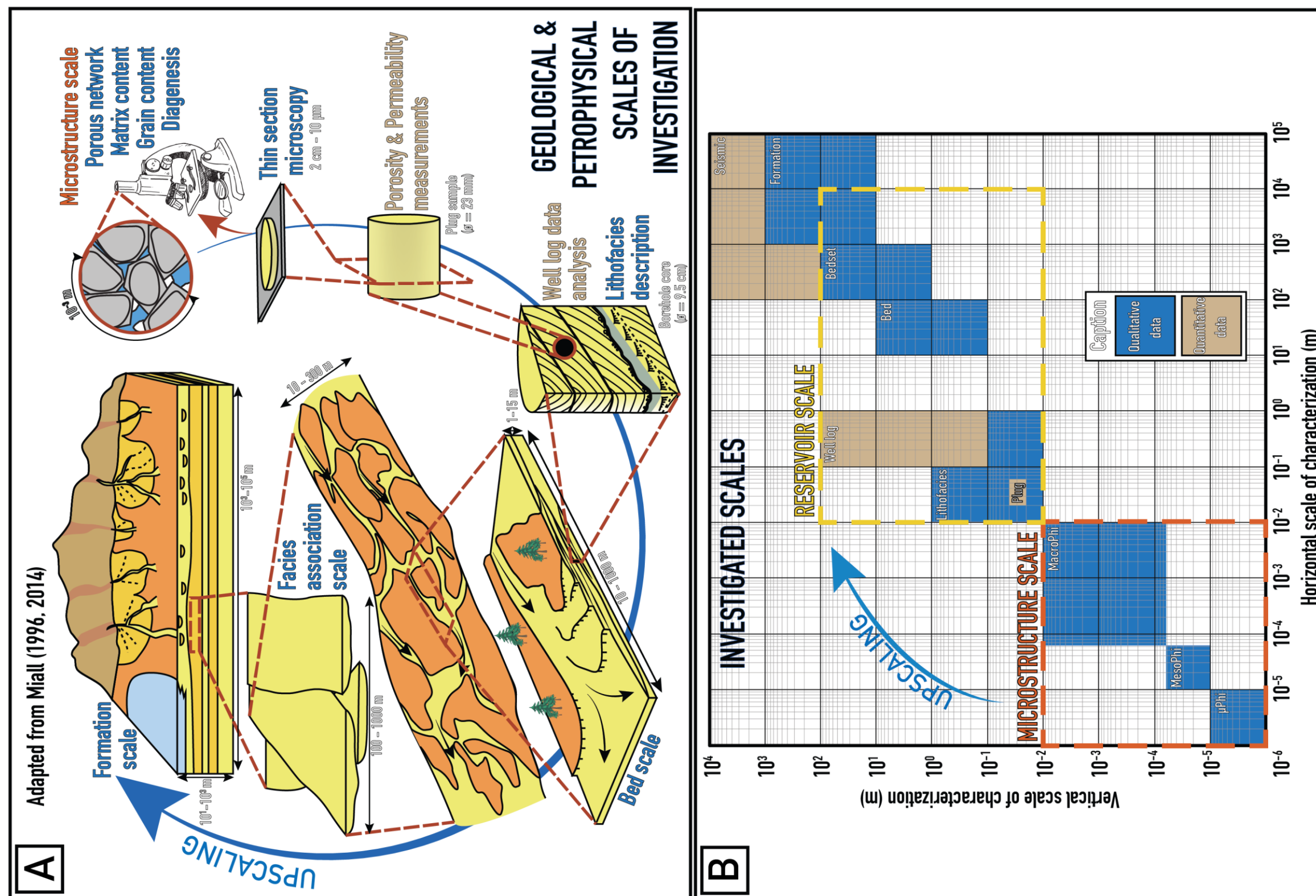


Figure 41: (A) Geological conceptual scales and (B) corresponded scales of data used in this deliverable.



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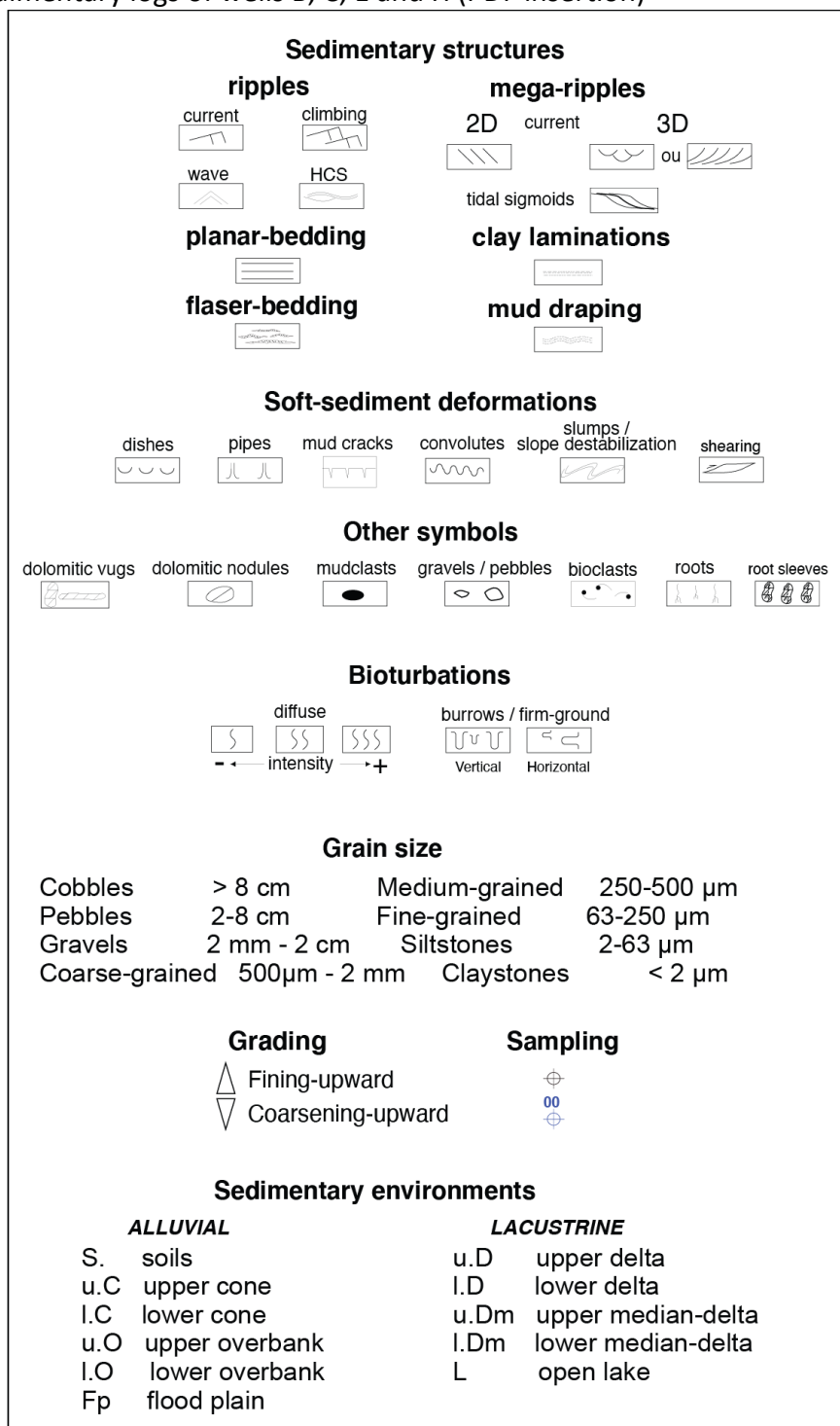
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### 3 ACKNOWLEDGMENT

*We acknowledge our collaborative partner Vermilion Energy who gave access to a large set of data and to their facilities in the frame of the MEET Project. This work benefited from stimulating and constructive discussions with C. Raddadi and V. Picornel for technical purposes and with E. Léoutre for management of our partnership.*

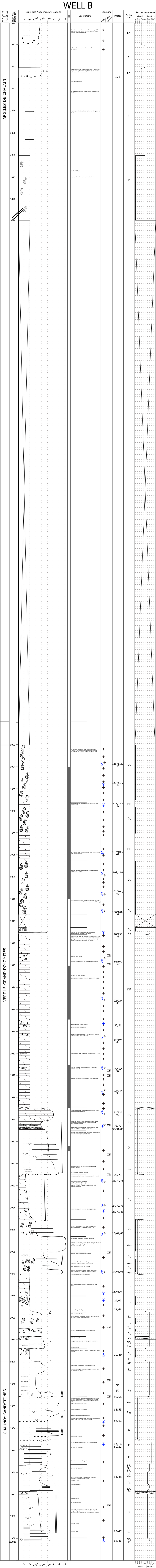
## 4 ANNEXES

### Annexe 1 - Sedimentary logs of wells B, C, E and H (PDF insertion)



Caption of sedimentary logs

WELL B





WELL C

Stratigraphy & Formations	Measured Depth (m)	Grain size / Sedimentary features								Oil	Descriptions	Sampling Purge Thi- sections	Photos	Facies codes	Sed. environments					
		Cl.	sl.	F. Sd	M.Sd	C.Sd	Gr.	Pe.	Co.						alluvial	lacustrine	glacial	marine	other	
	2108												572	FD						
	2109										Isolated pebbles		571 570	SF						
	2110										Alignment of soft pebbles		569							
	2111										Poorly sorted Qtz soft pebbles & dol. subrounded to subangular	01 02 03	568	Sh						
	2112										Alignment of pebbles and clays showing the stratification	04	567							
	2113										Alignment of soft pebbles Tapisage anguleux centimétrique		566 565 564							
	2114										Isolated granules & little pebbles		563							
	2115										Large quartz vein Oblong & lenticular dolomitic pebbles separated by clayed laminae	05 06	562 561	Dn						
	2116											07	560	Dn						
	2117										Deformed zone with large Qtz veins and red minerals, some relics of Gf		559 558	Dh						
	2118										Root sleeves vuggy	08 09	557 556	Dn						
	2119												555							
	2120										Dol. associated with bioturbation?	10 11	554 553							
	2121										Numerous small pyrites or white micas?		552 551	Shb						
	2122										Dolomitic congl. (Qtz, lithics (Df)	12	550	Gh						
	2123											13		Df						
	2124										Morceau de carotte qui semble concordant avec les boîtes K1-14 et K2-1		549							
	2125																			
	2126										Cristaux de dolomies rhomboédriques		548							
	2127										Bioturbation aspect	14 15	547 546	Df						
	2128										Isolated pebbles		545 544	Df						
	2129										Very poorly sorted	16 17	543 542	Smc						
	2130												541	Dn						
	2131										Very poorly sorted congl., polymictic, matrix supported (Gmu)	18 19	540 539							
	2132										Large angular dolomitic elements		538	SD						
	2133										Dolomite within microcracks		537 536	Df						
	2134										Dolomitic rhomboedre within a large vug	20 21	535 531-534 530 529	Dh						
	2135										Very poorly sorted		528	Gmu						
	2136										Angular to sub-angular pebbles									
	2137										Some sleeves & lot's of microcracks		527	Dn						
	2138										Red pebbles	22	526							
	2139										Dolomite within microcracks		525							
2140										Qtz granules Gmu facies		524	Df							
2141										Large pebbles subrounded to angular	23	523 522 521	Dh							
2142										Very poorly sorted, polymictic	24	520	Dn							
2143										Impregnated pebbles										
2144										Stylolites associated with clays	25	519	SD							
2145										Some dolomitic veins subhorizontal		518								
2146										Dolomitic elements with a lenticular geometry between the stylolites	26	517	Gi							
2147										Reddish clayed matrix		515								
2148										Very poorly sorted congl., matrix supp. with a dolomitic cement at its base	27 28	512 511	SD							
2149										Large oncoid at the base of the congl. Within the dolomite levels		510	Da							
2150										Vugs more abundant within the cemented zones	29	509								
2151										Root with central zone totally dissolved	30 31	508 507	SD							
2152										No stylolites and massive!										
2153										Small dolomitic nodules	32	506	Sho							
2154										No stylolites and massive!		505	Shb							
2155										Vuggy level	33 34	504 503	Dn							
2156										Cementation/Replacement of the sandstone										
2157										Vuggy at the base, without stylolites and massive!	35	502								
2158										Pyrite associated with limpid minerals (Qtz?)		501	Shb							
2159												499								
2160										Some granules and soft pebbles		498	Gmy							
2161										Lenticular sandstones/Floaser alternating with decalcification clays		497	Gh							
2162										Very vuggy at the base		496	?							
2163										Slightly erosive base		495	Sh							
2164										Some vugs		494								
2165										Dendroformes figs		493	SF							
2166										Bioturbation aspect		492	SF							
2167										Some small vugs		491								
2168										Pebbles and Gf lenses within a clayed matrix		490	Sh							
2169										Very vuggy		488/489	Gmu							
2170										When pebbles are dissolved, girdles formation		487								
2171											36	486	Gmu							
2172										Very vuggy blocs	37	485								
2173										Polymictic congl., very poorly sorted										
2174																				
2175										Very vuggy, big clayed pebbles vanished										
2176										Very poorly sorted										
2177										Some Gm levels poorly sorted										
2178																				
2179										Very poorly sorted matrix Gg -										
2180										Gf angular at the base										







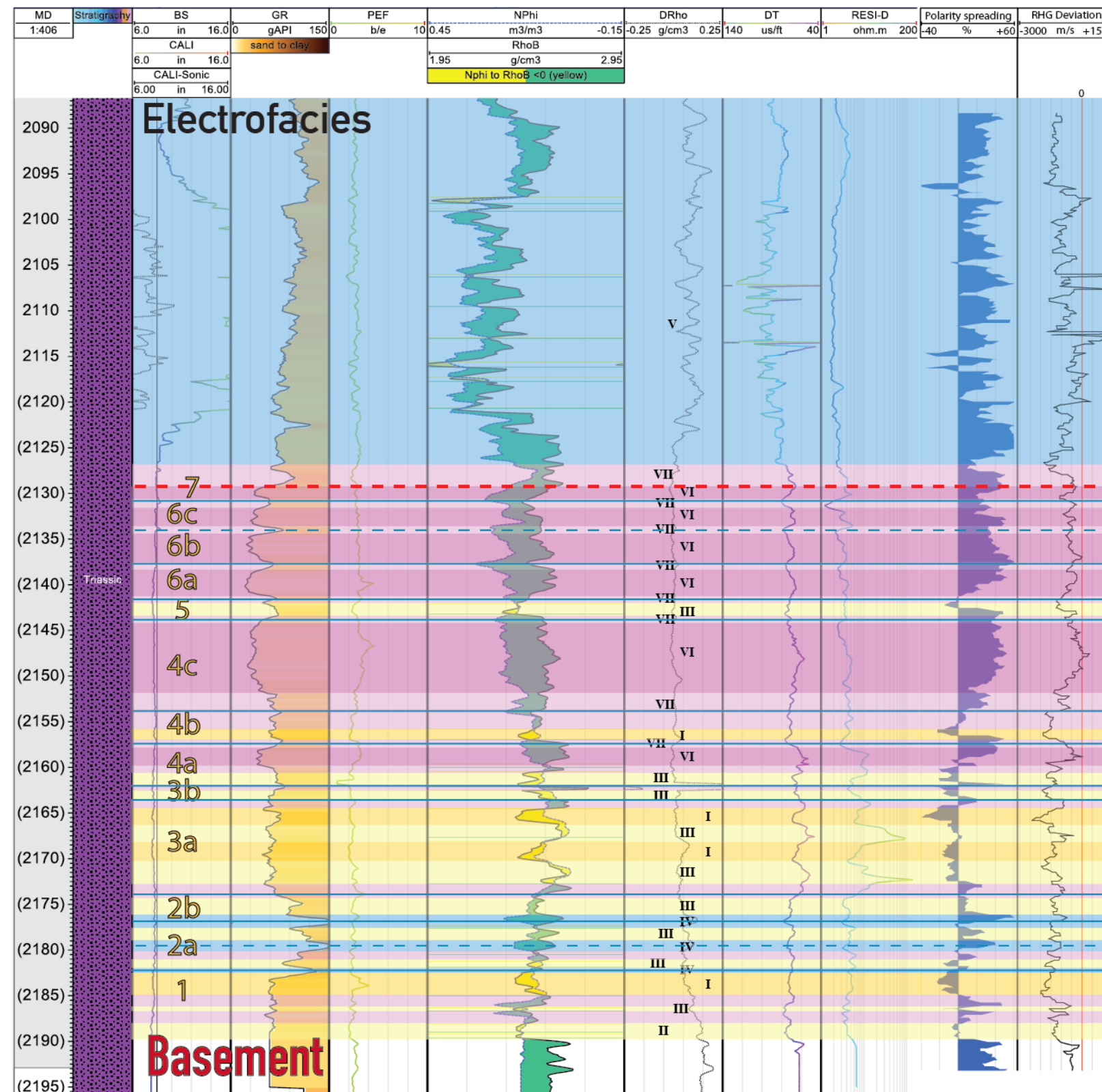
# WELL H

WELL H									
Stratigraphy & Formations	Measured Depth (m)	Grain size / Sedimentary features	Oil	Descriptions	Sampling	Photos	Facies codes	Sed. environments	
								alluvial	lacustrine
ARGILES DE CHALAIN	1979			red dolomitic siltstones, green zones with clear hilly patterns, nodules of grey silty dolomitic laminae with brachiopod fragments (brachiopods, lamellibranch ?), muds					
	1980			some isolated elements with similar nature of the underlying conglomerate			F		
	1981			poorly-sorted conglomerate with joint roughly polygenic components in a red clayish-silty matrix (quartz, dolomite, siliceous pebbles), dolomitic elements showing pressure-solution figures		686/689	G <sub>n</sub>		
				dolomitic red clays, locally green					
	1982			dolomitic nodules and truncated layers some fragments of fauna and sealed microfractures		685	FD		
	1983			grey dolomite (dolomicrospar) with dissolution figures, veins filled with overlying clay		684	D <sub>n</sub>		
				green clayey nodules toward dark red silty laminae					
				dolomitic nodules with quartz veins		682/683	FD		
				abundant angular clay pebbles					
						680/681	SD <sub>r</sub>		
SUPRA-DOLOMITIC SANDSTONES	1985			fine sandstones, light grey to white, with dolomitic cement, showing coarse (up to 30 mm) rough cross-bedding, dark red to brown siltstone interbedded		679	FD		
				brown red siltstones with dolomitic nodules, dolomitic veins with dissolution figures, slightly sandy (root traces?)					
	1986					678			
				grey dolomite with dissolution figures filled with overlying clay/silts, regular undulations at the base (riples?)					
	1987			fine to medium-grained sandstones, green to light green thin laminae, locally water-escape figures			S <sub>n</sub>		
				disturbed aspect		677	S <sub>t</sub> ?		
						676			
	1988			dark brown coarse-grained subangular sandstones quartz, feldspar and mica elements	01	675			
				zone with brown-red holes in sandstones (cavities)		674	S <sub>m</sub>		
				brown-red dark friable sandstones	02	673	D <sub>n</sub>		
	1989					669	S <sub>m</sub>		
				black clayish siltstones with very abundant stick-silicates		668			
				small coalescent nodules		667	F <sub>n</sub>		
	1990			grey dolomite with dissolution figures, black clay and sandstone filling, isometric dolomicrospar		666			
				reworked dolomitic elements in a thin subangular conglomeratic layer		665	D <sub>n</sub>		
				brown-red siltstones		664	G <sub>mu</sub>		
				coalescent nodules and pinkish dolomitic pebbles wrapped in a beige microsparitic dolomite		663	F <sub>n</sub>		
				grey dolomite with dissolution figures, green clay and locally fine filling, slightly sandy, locally some microfractures, truncated aspect, nodules at the base, dissolution area marked by horizontal reworked vugs					
				red minerals		662	D <sub>n</sub>		
				big pebbles at the base		661			
VERT-LE-GRAND DOLOMITES	1998			polygenic grey conglomerate with dolomitic cement, washed, cone-like aspect, both with green sandy matrix, some hard pebbles replaced by dolomite		672	G <sub>mu</sub>		
				polygenic, matrix-supported, subrounded to subangular		671			
				poorly-sorted conglomerate with silty-sandy matrix		670			
	1999			washed grey dolomite (dolomicrospar), cone-like aspect, very intense dissolution vugs filled by clayish sandstones and green clay, locally black clay		660	D <sub>r</sub>		
				vuggy with abundant dissolution planes		659			
	2000					658	D <sub>n</sub>		
						657			
				dolomite with very abundant dissolution planes and vugs filled by green clayish sandstones		656			
	2002			very vuggy					
				green sandstones with dolomitic cement, locally well-developed, petaloid dolomitic laminae at the top			D <sub>n</sub>		
	2003			isolated pebbles					
				dark green sandstones, tension cracks with dolomitic		655			
				grey dolomite with very high dissolution, brecciated at the top, continuous vugs/dissolution planes, green sandstones filling					
	2004			precipitation of transparent crest minerals on a red matrix		652/654			
				green to grey sandstone, locally dolomitic cement, well-sorted elements, quartz and feldspar		650	D <sub>n</sub>		
				progressive transition towards dolomite		649	D <sub>n</sub>		
	2005					648	S <sub>n</sub>		
				succession of conglomerate and green clayish medium-grained sandstones with fine-grained persequences					
				abundant pink quartz		647	S <sub>n</sub>		
				very poorly-sorted conglomerate		646	G <sub>h</sub>		
	2007			dolomitic cement					
				abundant basement and pinkish quartz pebbles		645	D <sub>n</sub>		
				dolomitic cement		644	G <sub>mu</sub>		
				sequence of - brown medium sandstones with dolomitic cements, petaloid mineralizations and dissolution figures - beige dolomite with some medium quartz - light beige yellow to dark white sandstone, in cm-thick (bedding), and very compact (dolomites?) dolomite with abundant dissolution figures		643			
	2008			dolomitic pebbles wrapped in a dolomitic cement, crosscut by dolomitic veins		642			
				truncated aspect					
				quartz veins, planar vugs with polyphased filling (chert/mudstone)		640/641	D <sub>n</sub>		
				very abundant vugs		639			
	2009			abundant voids filled with crest-type minerals (dolomite)		638			
				horizontal red vein		637	D <sub>n</sub> (?)		
	2010			conglomerate with dolomitic cement, and abundant green minerals		636			
				yellowish gravel sandstone		635	G <sub>n</sub>		
				clayites always on the top edge of dolomitic veins		634			
				dolomitic pebbles wrapped in dolomitic cement		633	G <sub>n</sub>		
	2012			abundant greenish basement pebbles		632			
				presence of dolomitic pebbles and big dolomitic nodules		631	S <sub>n</sub>		
				beige and greenish green dolomicrospar, violet at the base, sandy and compact		630	SD		
				abundant vugs parallel to the bedding		629			
				rough bioturbation	04	628			
				isolated pebbles		627	S <sub>n</sub>		
	2013								
						626	S <sub>n</sub>		
				coarse-grained sandstones with conglomeratic "best", green (tan brown, green mudclasts and feldspars)		625			
				very well-sorted medium sandstones, green or beige, violet dominant, colour-coded and halo around microfractures, dolomitic cement		624	SD		
	2014			riples disappear with the precipitation of dolomite		623			
				well-sorted medium sandstones, grey at the top and coloured toward the base, with violet-dominant, colour-coded and halo along microfractures, dolomitic cement		622	SD		
				well-sorted, partially dolomitised		621	SF		
				convoluted laminated bedding with very fine pinkish sandstones and green sandy clay		620	G <sub>mu</sub>		
	2015			very tiny mudclasts		619			
				few and less pebbles		618			
	2016			partially dolomitised, less cement toward the top		617			
				subangular to subrounded pebbles		616	F		
				dolomitic cement		615			
				poorly-sorted, matrix-supported (medium/coarse), polygenic conglomerate		614	S <sub>u</sub>		
				progressive transition		613			
	2017					612			
				disturbed aspect		611			
						610	S <sub>n</sub>		
				partially dolomitised		609			
				some small oxidised pyrites		608			
	2019			partially dolomitised		607			
				isolated gravels		606	SD		
	2020			small dolomitic and lenticular nodules		605	S <sub>b</sub>		
						604			
				well-sorted		603	S <sub>m</sub>		
						602			
	2021			flaser / lenticular		601	S <sub>n</sub>		
				flaser / lenticular		600			
				well-sorted		599			
				disturbed aspect		598			
	2022			angular pebbles		616			
						615	SF <sub>b</sub>		
	2023					614			
				quartz vein at the termination of a rootlet		613			
	2024					612			
				voids		611	SD		
				small spherical voids		610	S <sub>m</sub>		
	2025			fine sand, scattered medium elements, quartz and feldspars, green and brown red, green clayish laminae		609	SF		
						608			
				massic laminae, red clay followed by green clay		607	S <sub>n</sub>		
	2026			poorly-sorted sandstone, medium to coarse, with conglomeratic beds, green clayish beds		606			
						605			
	2027			massive calc-supported conglomerate without dolomitic structures, abundant altered and dissolved pebbles, voids are very frequent and often connected, zone with reddish matrix, some dolomitic elements, sandy-dolomitic cement, mineralisations		604	G <sub>n</sub>		
						603			
	2028					602			
				succession of three fine-upward detrital sequences (from 2028.6 to 2021.5m) - green clay (only the last sequence) - medium sandstone - thin conglomeratic lag		601	S <sub>m</sub>		
	2029			vuggy at the top		600	GD(?)		
				poorly-sorted polymeric conglomerate with dolomitic cement		599			
	2030					598			
				small nodules of dolomitic cement		597			
	2032			this layer of poorly-sorted conglomerate		596			
						595			
				medium sandstones, brown-coloured, some coarse oxidised elements, green clayish elements		594	S <sub>n</sub>		
	2033			clayish layer		593			
				clayish layer, overlaid by some mud clasts	06	592			
				opened fractures, residual bituminous remnants	07	591			
	2034								



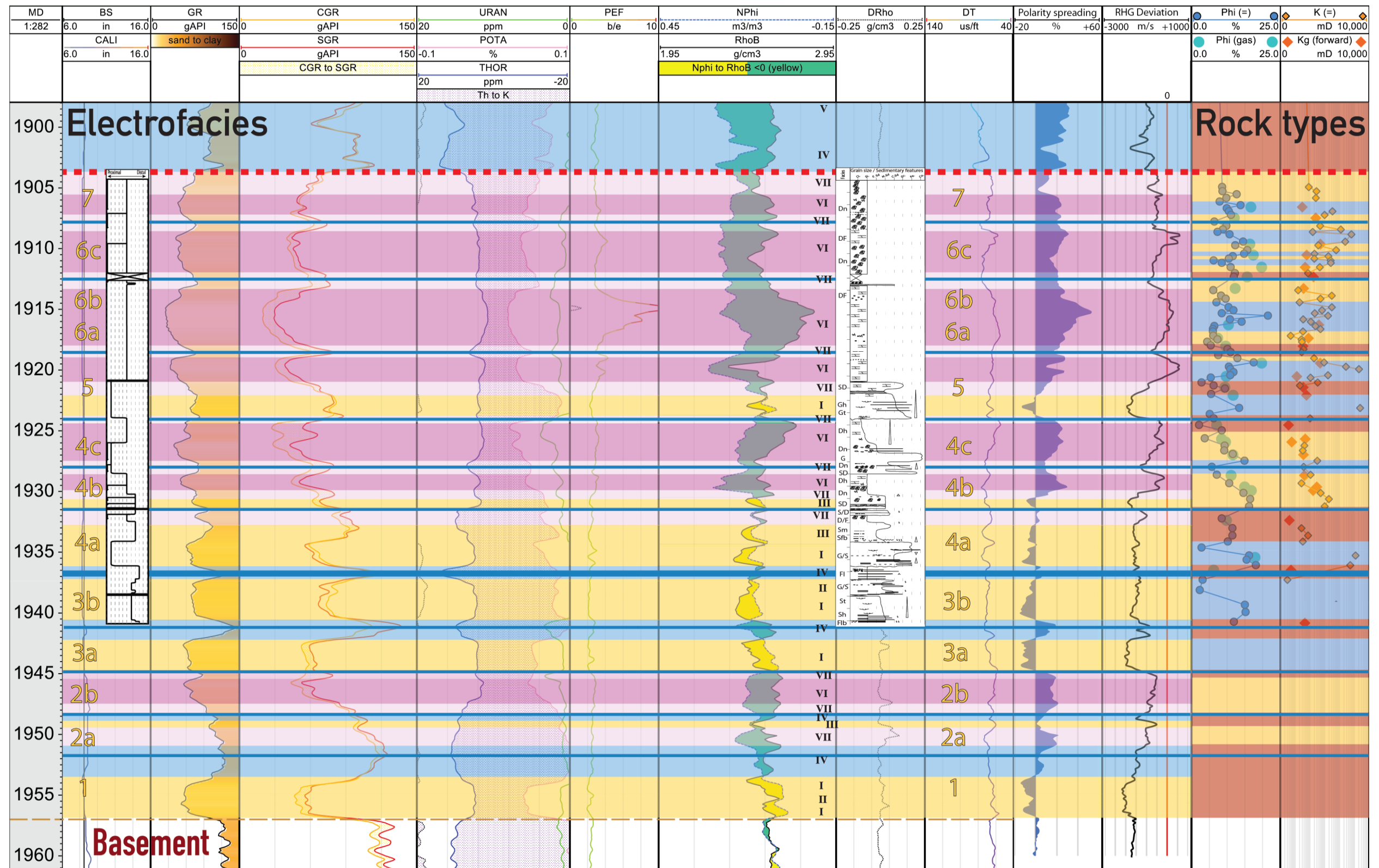
Annexe 2 – Electrofacies and rock typing of the whole studied wells (A, B, C, D, E, F, G & H), please see Figure 34 for the caption explanation.

# WELL A

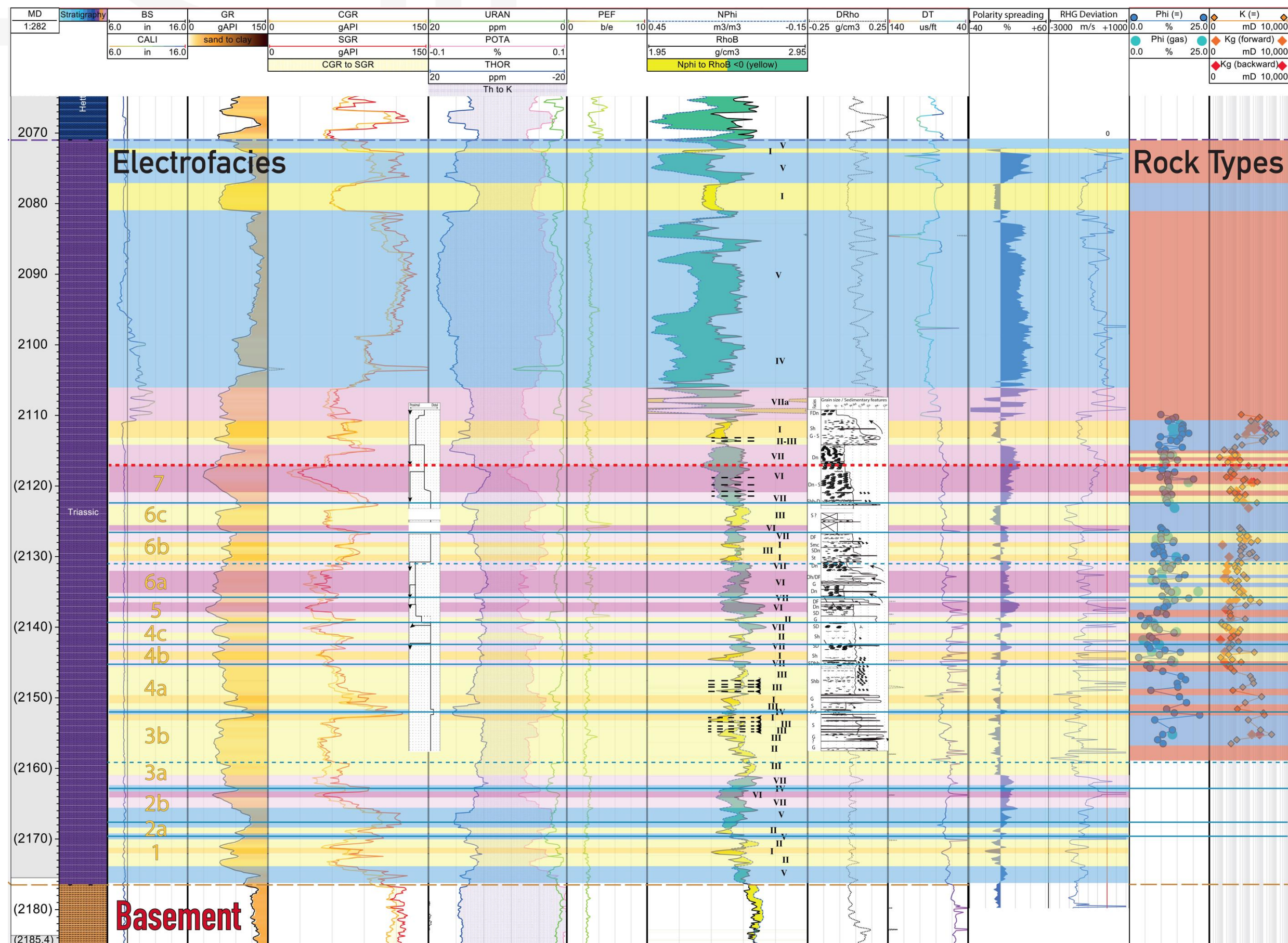




## WELL B

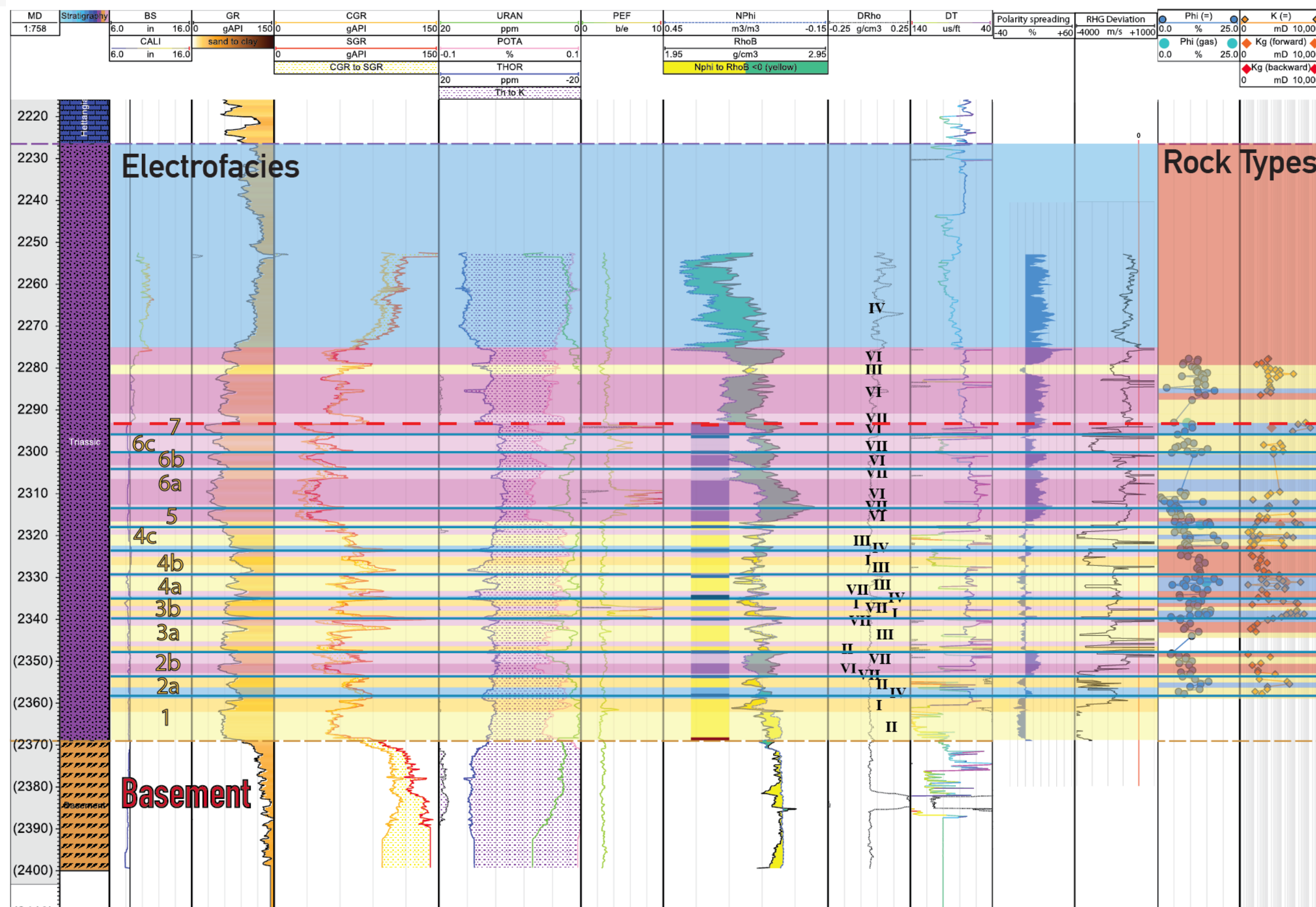






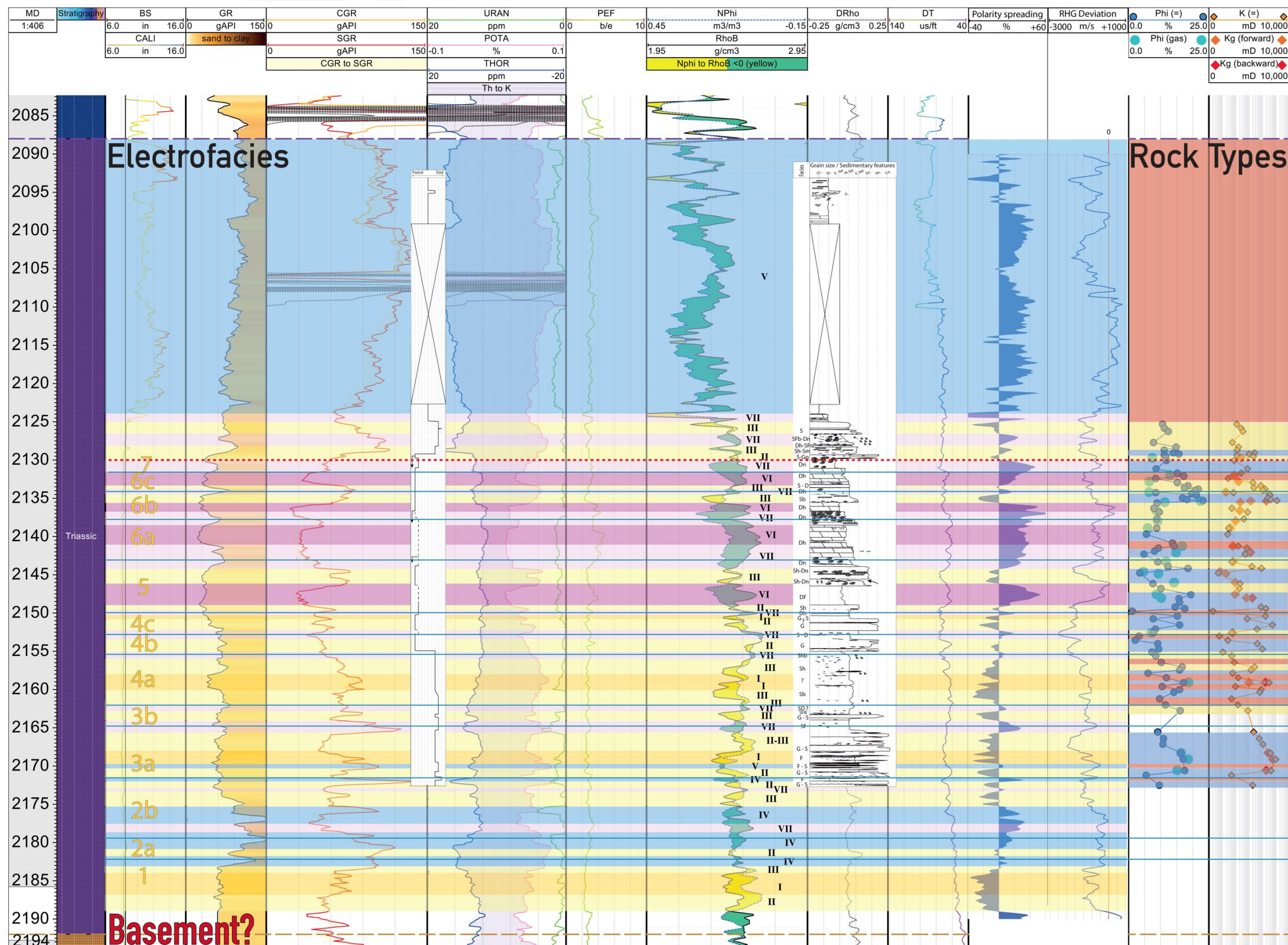


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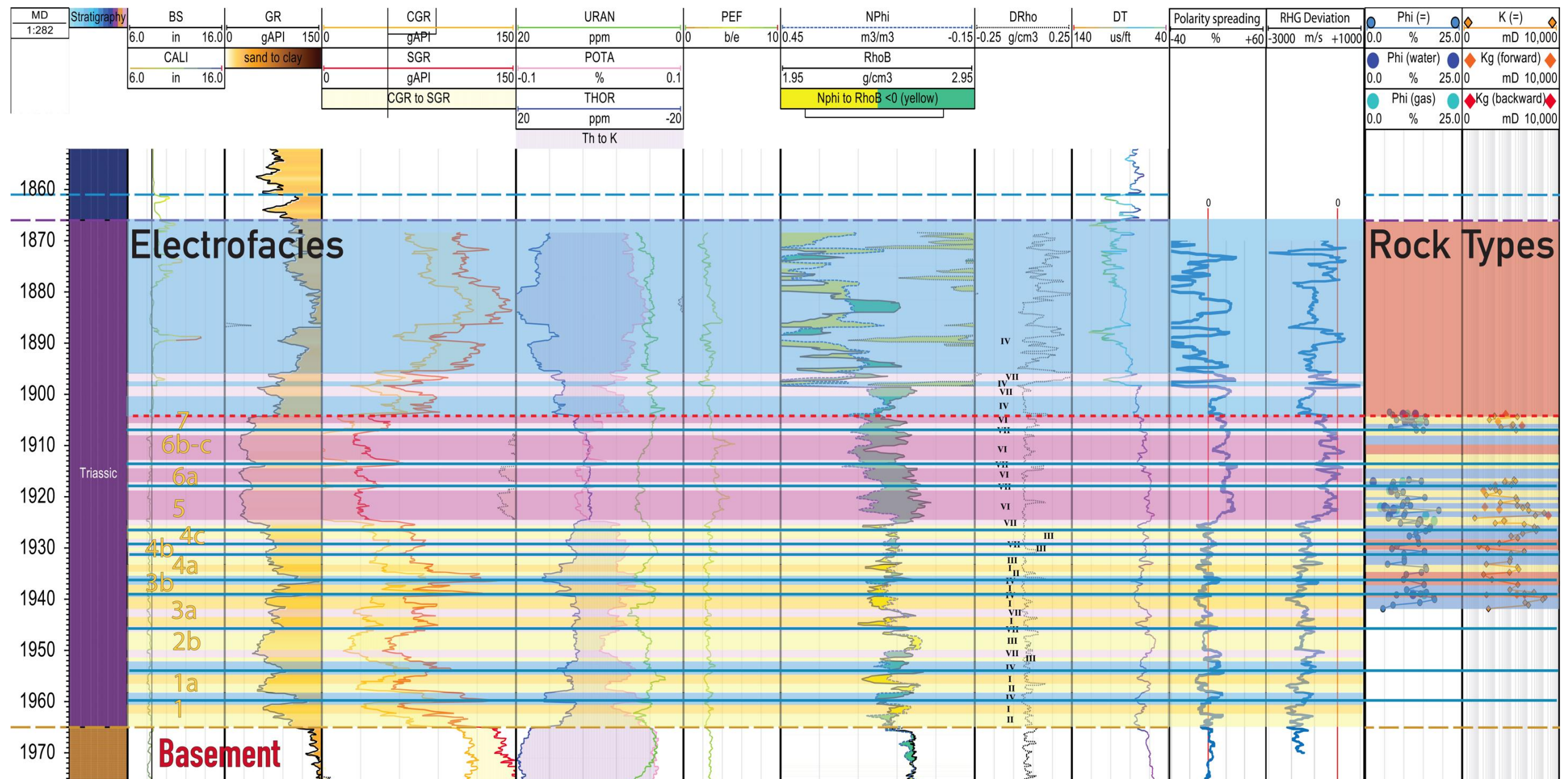


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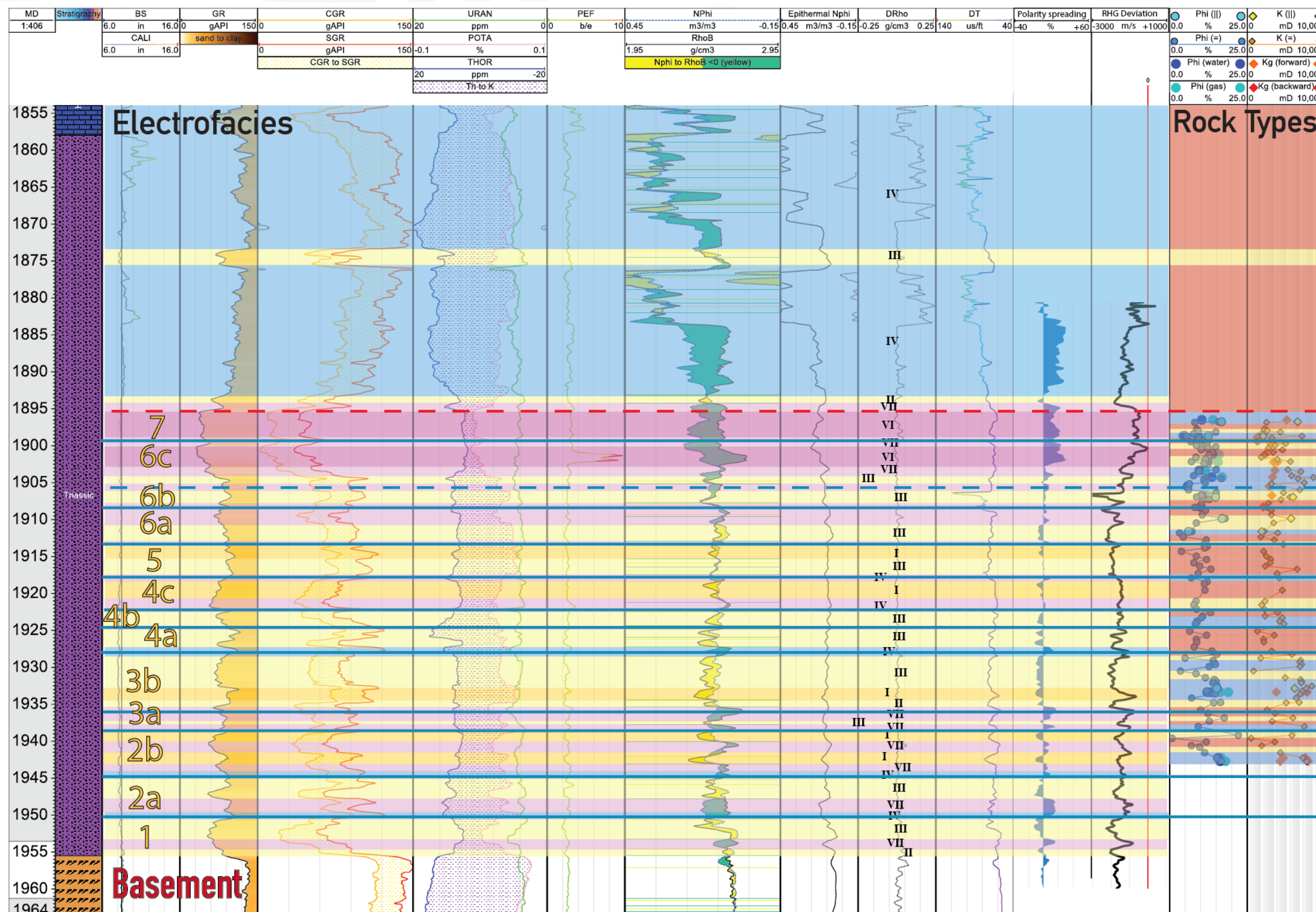


# WELL F



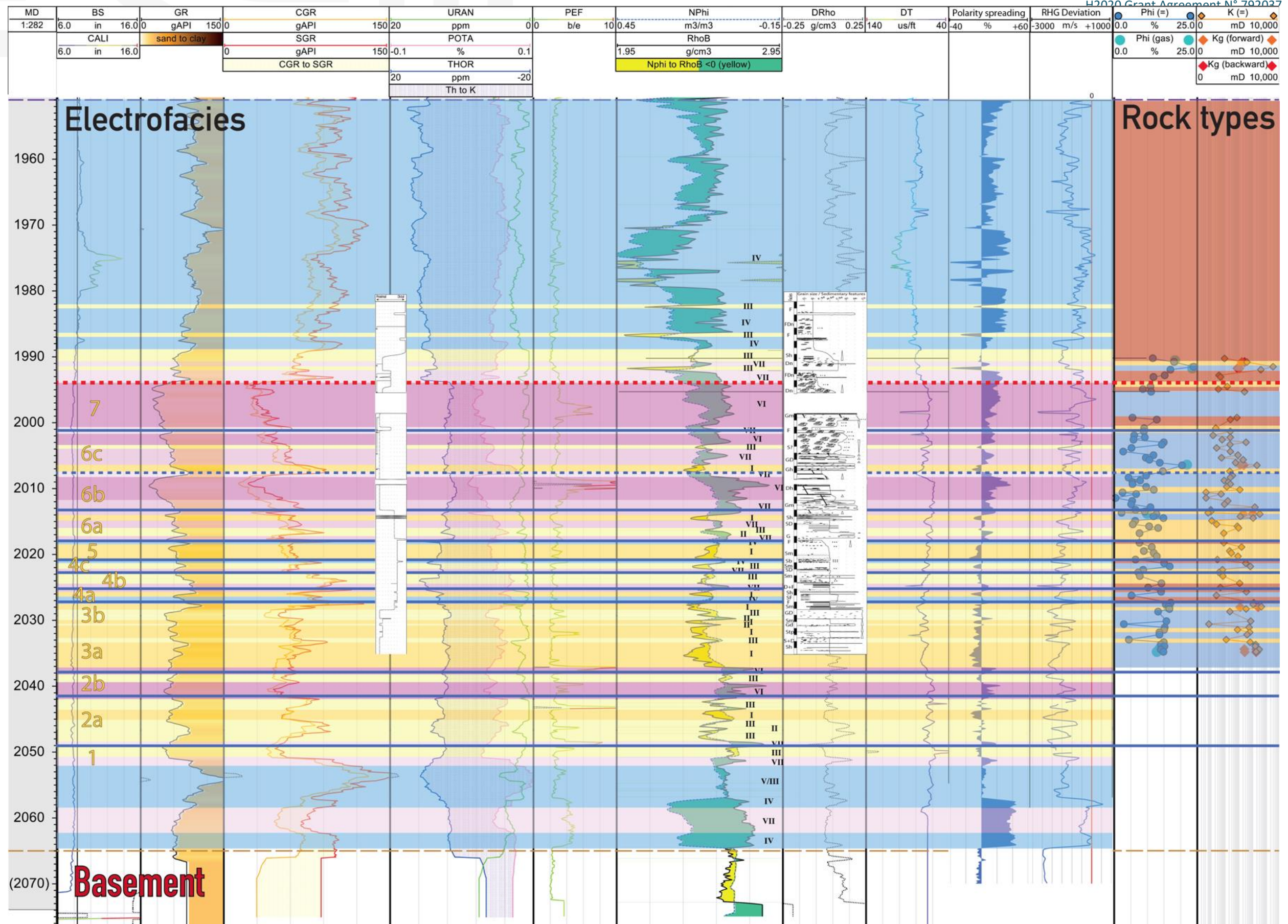


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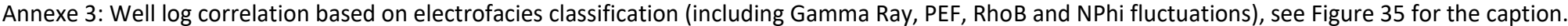




# WELL H







## Imprint

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Report Authorship	Bailly C., Sengelen X. et al., (2021). <a href="mailto:cedric.bailly@cyu.fr">cedric.bailly@cyu.fr</a> , <a href="mailto:xavier.sengelen@cyu.fr">xavier.sengelen@cyu.fr</a> Summary of petrophysical analysis, MEET report, Deliverable D3.6, January 2021, 91 pp.	
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