Quick look cathodoluminescence analyses and their impact on the interpretation of carbonate reservoirs. Case study of mid-Jurassic oolitic reservoirs in the Paris Basin

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Abstract: Cathodoluminescence analyses on samples from Middle Jurassic oolitic limestones allow us to reconstruct the diagenetic history of these oil and gas reservoirs: a succession of events starting with the early, synsedimentary phases of marine cementation and ending with the addition of hydrocarbons to the reservoir. Constraints on the timing of events are derived from their calibration with the chronology of the well-known regional tectonic calendar. Fracturing, due first to the post-Pyrenean extension and then to the Alpine compression, led respectively in Oligocene times to a recharge of the aquifer and a correlative change in cementation, and in Miocene times to the addition of hydrocarbons into the same flow units, this last event blocking diagenesis, at least in the zone above the oil-water contact. Distributions of cements and residual porosity within sedimentary units without stratigraphic significance, called here "pseudo-parasequences", were for the most part inherited from the original depositional facies.

Key Words: Cathodoluminescence; Middle Jurassic; Callovian; Paris basin; echinoderms; oolite; ooid; calcitic cement; porosity.

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Résumé : *Analyses rapides en cathodoluminescence et leur impact dans la compréhension des réservoirs carbonatés. Exemple de réservoirs oolithiques du Jurassique moyen du bassin de Paris.-* L'étude d'échantillons de calcaires oolithiques du Jurassique en cathodoluminescence a permis de reconstituer l'histoire diagénétique de ces réservoirs de pétrole et de gaz, c'est-à-dire l'enregistrement d'une succession d'événements débutant avec des phases précoces de cimentation marine, synsédimentaires, et s'achevant avec l'arrivée des hydrocarbures. Par corrélation avec le calendrier tectonique régional, relativement bien connu, ces événements ont pu être calés sur l'échelle stratigraphique. Les phases de fracturation, en relation avec la phase d'extension qui a succédé à la compression post-pyrénéenne, puis avec la compression alpine, ont conduit respectivement à l'Oligocène à recharger l'aquifère et par conséquent à modifier la cimentation, puis au Miocène à y introduire des hydrocarbures, ce dernier événement entraînant un arrêt de la diagenèse, au moins pour l'intervalle situé au-dessus du contact pétrole-eau. La répartition des ciments et celle de la porosité résiduelle au sein d'unités sédimentaires dépourvues de toute valeur stratigraphique, appelées ici "pseudo-paraséquences", sont en grande partie contraintes par le faciès initial de dépôt.

Mots-Clefs : Cathodoluminescence ; Jurassique moyen ; Callovien ; bassin de Paris ; échinodermes ; oolithe ; ooïde ; ciment calcitique ; porosité.

Introduction

The effective porosity of the oolitic reservoirs of the Paris Basin considered generally to be of Early Callovian age (they include the latest Bathonian as well) is essentially residual. It is the porosity still present in the intergranular spaces not filled completely by cement. Cathodoluminescence studies of these calcitic cements show that pore-filling proceeded in several steps. The integration of this paragenetic sequence with structural data permits a more or less precise reconstruction of the succession of stratigraphic events (among them

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cementation); moreover, the period of time during which hydrocarbons migrated into these reservoirs can be determined by a quick look analysis of the fluid inclusions in these cements. Finally, cathodoluminescence studies led to a model for the distribution of calcitic cements in "pseudo-parasequences", that is the reverse aspect of the distribution of their residual porosity. These several considerations are enlarged upon in the case study that follows.

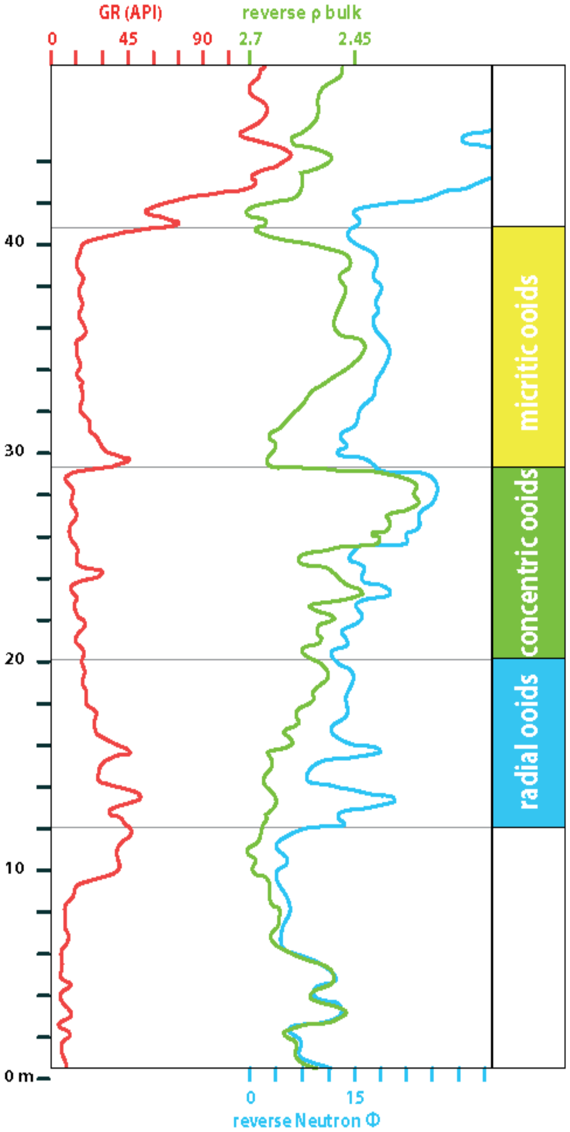


Figure 1: Log of a Fontaine-au-Bron field (modified from the Geopetrol website) documenting the three fold division of the Dalle Nacrée into a basal radial ooid unit, a median concentric ooid unit and a upper micritic ooid unit.

Stratigraphical and sedimentological settings: the concept of pseudo-parasequence

Oolitic facies attributed to the Lower Callovian are known in the subsurface of the Paris basin (the "Dalle Nacrée" or "Petite Oolithe" Formation), for example in the Villeperdue field where they are reservoirs (GRANIER, 1993, 1994a, 1994b, 1994c, 1994d, 1995, and a number of unpublished Total reports), and in outcrop in Burgundy (in the Pierre de Dijon-Corton and Pierre de Ladoix formations: LAVILLE *et alii*, 1989).

The subdivision of these formations and their interpretation in terms of sequence stratigraphy has given rise to various hypotheses. For instance, in the Villeperdue field, about a hundred kilometers east of Paris, GRANIER (1993, *et sequitur*) subdivides the "Dalle Nacrée" into three units, from bottom to top (Fig. 1): 1) a unit of radiate ooids with at their base the subaerial exposure surface capping the Upper Bathonian Comblanchian Formation, 2) a unit of concentric ooids and 3) a unit of micritic ooids. These three units represent three parasequences of the lowermost "Callovian" transgressive systems tract. These shallowing upward sequences are separated by major sedimentary discontinuities, that is to say they are regional in extent, generated by allocyclic phenomena, and interpreted as time-lines (contrary to the opinion of PURSER, 1969). These discontinuities have served as golden spikes for correlation of the entire Villeperdue field and for neighboring off-structure wells; they permitted breaking it up into three reservoir units corresponding to the three stratigraphic units defined by the texture of the ooids.

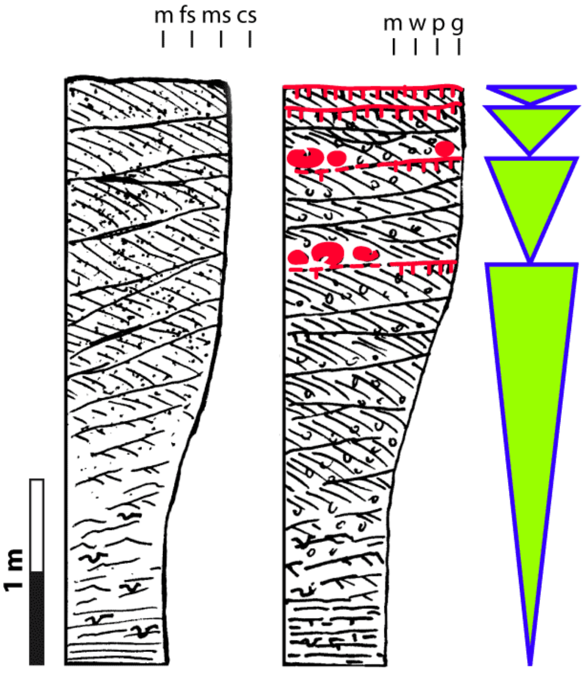


Figure 2: Comparison of a siliciclastic parasequence (left) and a carbonate parasequence (right). The carbonate parasequence can be divided into 4 "pseudo-parasequences" on the basis of the occurrence of early diagenetic discontinuities (hardgrounds and derived intraclasts) as indicated in red.

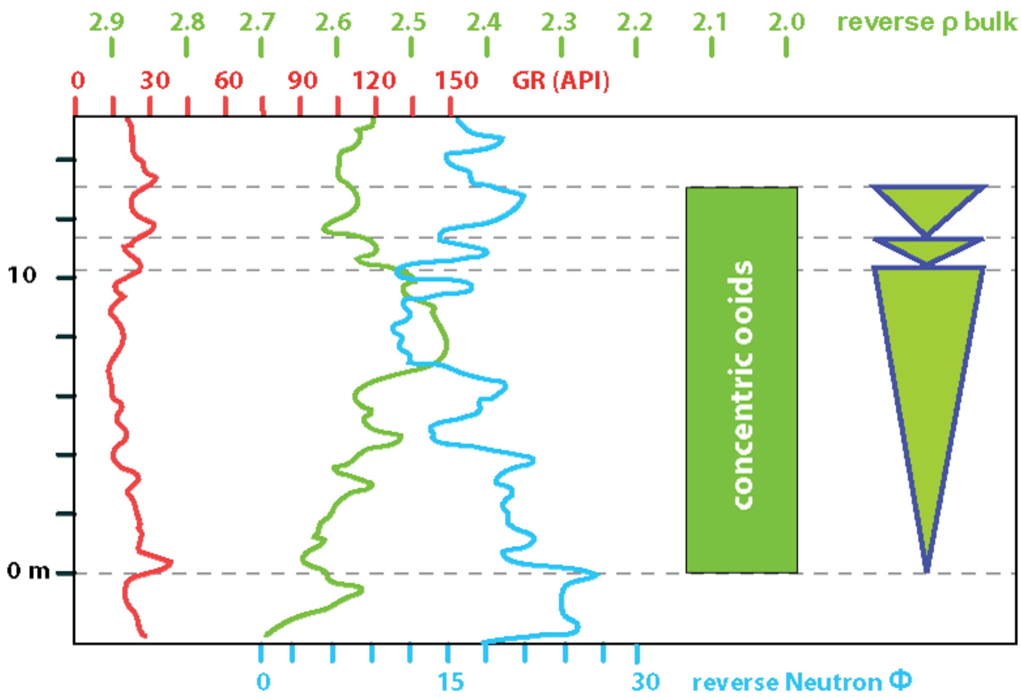


Figure 3: Example of a well log illustrating a single carbonate parasequence (unit with concentric ooids) divided into 3 "pseudo-parasequences" (well "T", field "T", east of Paris).

Oolitic and bioclastic parasequences differ significantly from siliciclastic parasequences laid down in similar environments (Fig. 2) for they include internal discontinuities caused by the early cementation of carbonates: hardgrounds (perforated and/or encrusted) or erosion surfaces associated with levels of gravel, pebbles, and/or cobbles that are also perforated and/or encrusted). These "local" discontinuities of course are not seen in siliciclastic rocks. In high-energy oolitic or bioclastic environments they are related to autocyclic phenomena and consequently they are correlatable for only ten meters or so as documented by both subsurface data in the Villeperdue and neighbouring fields (GRANIER, 1993, *et sequitur*) and outcrop analogs in Burgundy (GILI, unpublished Total report; GRANIER, 1993, *et sequitur*). As they have no stratigraphic value, they have been called "pseudo-parasequences" (GRANIER, 1993): bounded by two well-marked discontinuities of which at least one is of autocyclic origin, they consist either of a simple sand wave or of several superposed sand waves (Figs. 2-3). JAVAUX (1992) and GARCIA (1993) gave a stratigraphic value to these discontinuities and to the "subunits" they bound, while other authors of the "Dijon school", LAVILLE *et alii* (1989) for example, did not make this error.

Note: According to J.C. van WAGONER (1985), a parasequence is "a relatively conformable succession of genetically related beds or bedsets bounded by marine-flooding surfaces and their correlative surfaces". Both bounding discontinuities are of allocyclic origin.

Pore filling versus residual porosity

Remarks on echinoderm debris and its associated cements

One category of bioclasts is particularly important. It consists entirely of echinoderm fragments (echinoids, ophiuroids, asterids, crinoids, holothurians) for each of these calcitic bioclasts behaves optically as if it was a single crystal (LUCIA, 1962; EVAMY & SHEARMAN, 1965, 1969). When these bioclasts are neither micritized (lined by a thin micritic film; see supplementary material on Figs. 21-26) nor coated to form the nuclei of ooids they are capable of acting as "germs" for calcite cementation (Fig. 4). Sometimes, as stated by EVAMY & SHEARMAN (1965), overgrowths were "gradually taking on a prismatic crystal habit" (Figs. 4 & 23-24). Syntaxial cements developed at their peripheries are much wider than those formed on the surface of other kinds of grain (Figs. 4-7); in the literature they are also known as "rim", poecilitic or poikilotopic cements. Hence, these echinoderm fragments are particularly deleterious to the maintenance of porosity; in other words they are "porosity killers" (on the other hand a moderate syntaxial cementation may prevent or diminish the impact of compaction, another "porosity killer").

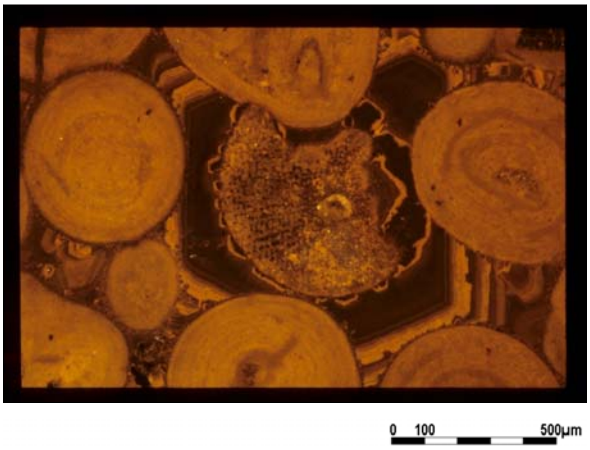


Figure 4: Syntaxial cement overgrowths on an echinoderm fragment (possibly an echinoid spine) with a monocrystalline behavior [they are not monocrystalline, but behave as if they were]. This bioclast was eroded, possibly bio-eroded, but discrete rates of cementation on the monocrystal faces "quickly" masked the corroded surface. This phenomenon is poorly developed during the early phases represented here by the succession of brown, orange, dark brown to black (non-luminescent) phases of cementation, but better illustrated in the next alternating phases, brown zoned and orange zoned. Note the very small quantity of cement on allochems other than echinoid fragments (mainly ooids).
(Ref.: 4.15X5) (well "S", field "S", east of Paris)

Main stages of pore filling

The syntaxial cements developed around these echinodermic bioclasts register in detail all the phases of cementation that affected the reservoir. Here, their examination by cathodoluminescence made it possible to outline the paragenetic sequence, that is, to define precisely three main stages of calcitic cementation (Fig. 8):

- the first step involves the phases of early cementation (synsedimentary diagenesis). Because the core was taken in a porous interval that shows no evidence of early lithification such as borings in hardgrounds, the importance of synsedimentary diagenesis is hard to determine. Generally poorly developed, these early-stage cements exist mainly around echinoderm fragments. At a hardground in a nearby well the following succession of cathodoluminescence was detected: brown, dark orange brown, zoned orange (yellow), brown, light orange brown, dark brown to black (non-luminescent), thus suggesting significant changes in the successive water chemistries. Commonly, only the last phase, dark brown to black (non-luminescent) is identifiable;

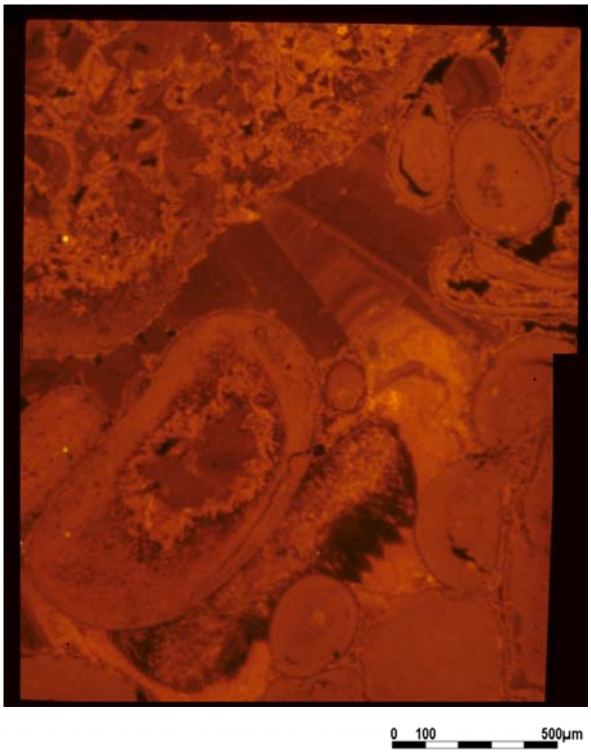


Figure 5: Syntaxial cement overgrowth on an echinoderm fragment acting as a single crystal : 1) early phases of cementation (synsedimentary diagenesis) of which only the last phase, dark brown to black (non-luminescent), is clearly identifiable; 2) intermediate phases of cementation characterized by a predominance of orange color, with some thin zones having brownish tones. Two of these darker colored bands provide a remarkably good marker; 3) late phases of cementation are predominantly brown, with more or less diffuse zonation.
(Ref.: 205828X5) (well "X", field "X", east of Paris)

- the second step involves intermediate phases of cementation that are distinguished by a predominance of orange. Some thin zones are brownish, thus probably indicating a slowdown in the rate of cementation. Two of these darker phases in a predominantly orange sequence provide an excellent marker (Fig. 5);
- the third step, involving late phases of sedimentation, is characterized by a predominance of brown. These phases are more or less diffusely zoned, suggesting a rather homogeneous chemistry of the aquifer throughout that interval of time.

Once recognized, this succession of color stages makes it possible to relate them to some of the events that occurred during the geologic history of the reservoir, an issue that will be addressed in the chapter "Relation to chronology".

Remark: Although Fe and Mn are present in the cathodoluminescence of the calcite (AMIEUX, 1982; MACHEL & BURTON, 1991; MACHEL *et alii*, 1991; BARBIN, 2000), analysis of which would have given us more information on the invading fluids, we did not consider such analyses here as we were only making quick look analyses.

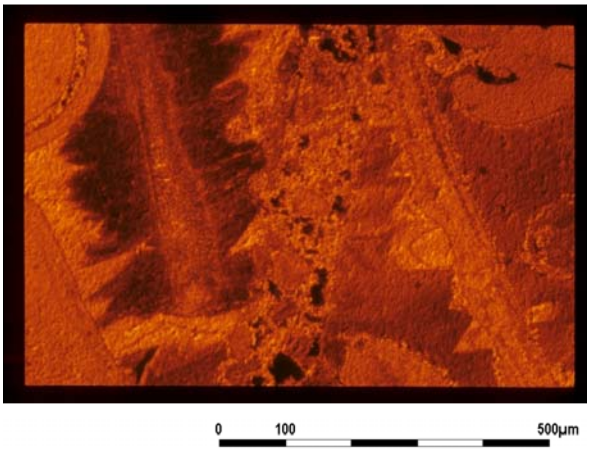


Figure 6: Syntaxial cement overgrowths on echinoderm fragments with a monocrystalline behavior. The fragment on the right was micritized: this envelope, in part organic, prevented locally the development of the early phases of cementation represented by a dark brown to black phase (not-luminescent) around it. However, this phase is visible around the second fragment, the one on the left.
(Ref.: 205828X10) (well "X", field "X", east of Paris)

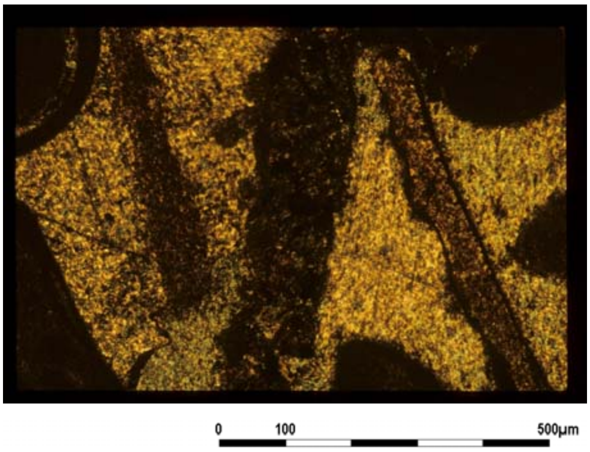


Figure 7: The preceding figure viewed under conventional transmitted light.
(Ref.: 205828X10) (well "X", field "X", east of Paris)
With the exception of this figure, all microscopic views were produced by cathodoluminescence.

Distribution of porosity in the pseudo-parasequences

The effective porosity of the reservoirs is for the most part residual, that is void space between the grains that still exists because intergranular pores are not completely filled by cement. Many intergranular pores may have been completely blocked before the last phases of cementation occurred, so additional cementation therein was impossible. For example, in a hardground early cements may occupy all the intergranular space. Therefore a last group of factors controlling the distribution of porosity is related to the thickness of the pseudo-parasequences and the way they terminate (in essence, their roof). Figure 9 represents a virtual/idealized oobioclastic pseudo-parasequence, that is an intermediate between an ideal oolitic parasequence and an ideal bioclastic pseudo-parasequence. Two fundamental types can be distinguished:

- pseudo-parasequence type 1, capped by a more or less well-developed hard ground,
- pseudo-parasequence type 2, truncated by an erosion surface covered by a level of reworked material, *i.e.* intraclasts (pebbles and gravel).

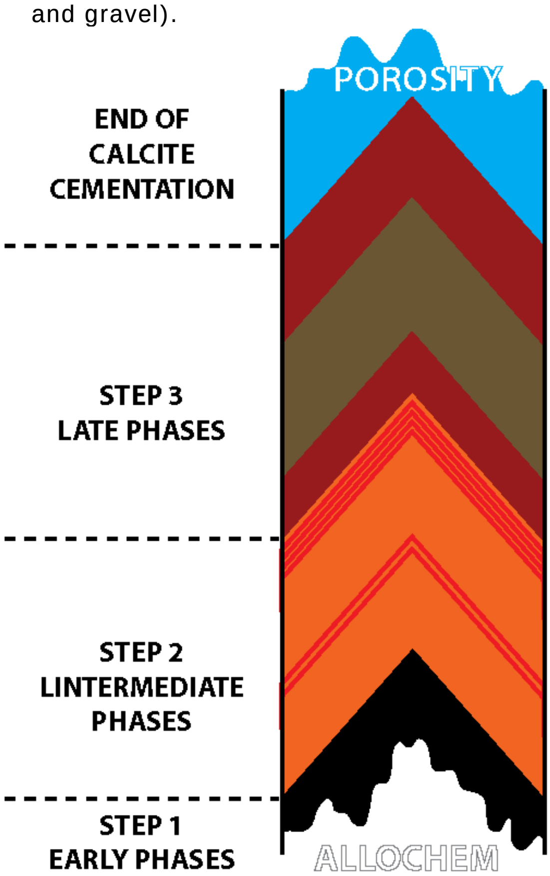


Figure 8: Diagenetic log (stratigraphic succession of the phases of cementation) used to establish the paragenetic sequence.

In an expanded pseudo-parasequence (Fig. 9 top) early cementation predominates near the upper limit. Although residual porosity is practically absent in an ideal bioclastic sequence (A3), it is well developed in the ideal oolitic sequence (A1), and in the mixed (oobioclastic) sequence (A2).

In a shortened pseudo-parasequence (Fig. 9 middle) the interval with residual porosity is also reduced in length (B1-B2-B3). As in the preceding, early cementation is better developed near the top.

In the truncated version, where the succession is topped by an erosion surface (Fig. 9 bottom), residual porosity exists up to the top in the oolitic or oobioclastic sequences (C1-C2). The levels that were involved in early cementation have been removed by erosion and probably contributed intraclasts (pebbles and cobbles) to the base of the overlying pseudo-parasequence.

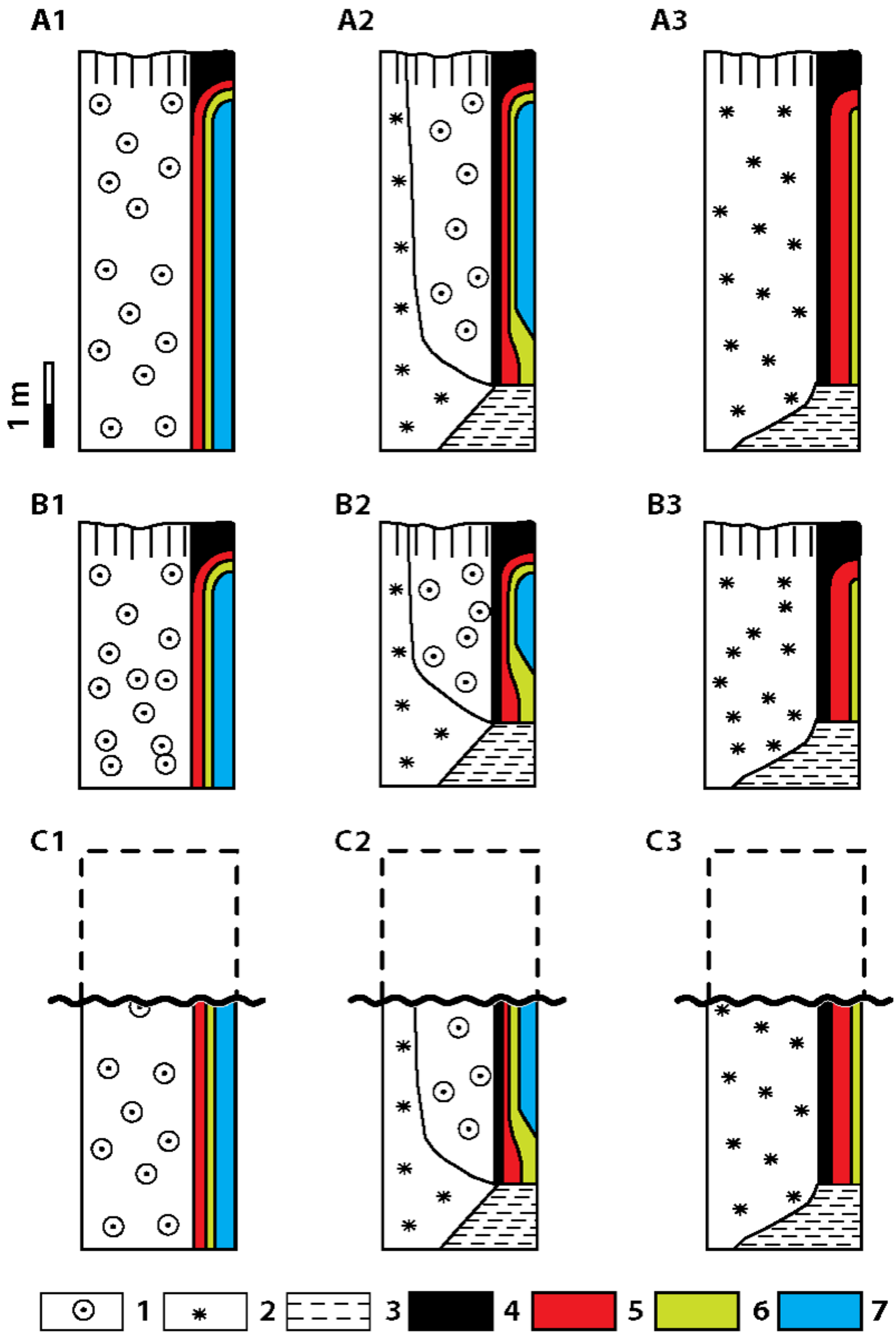
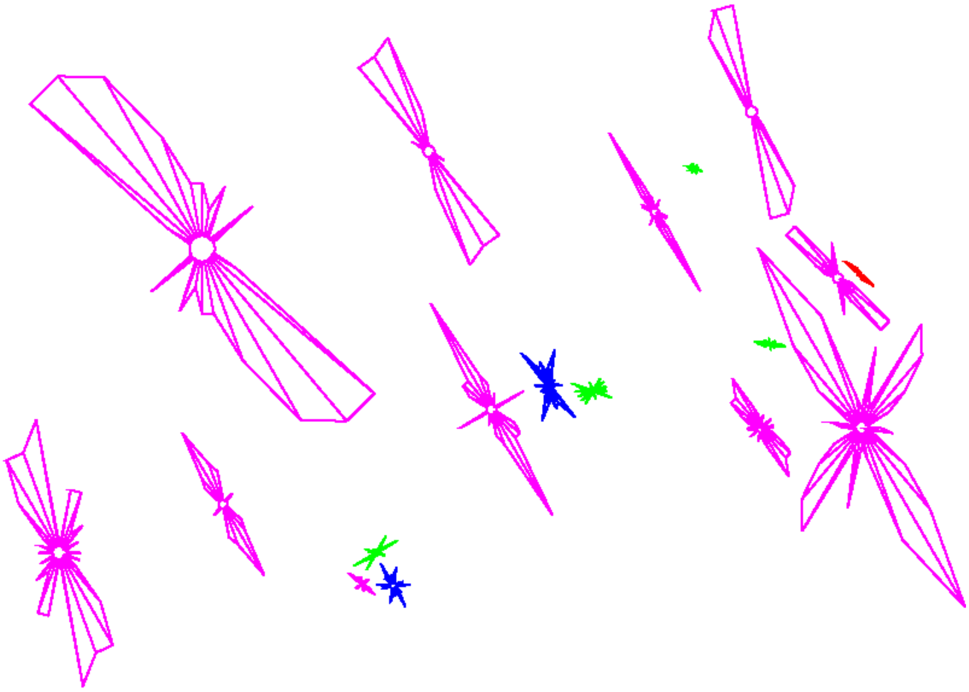
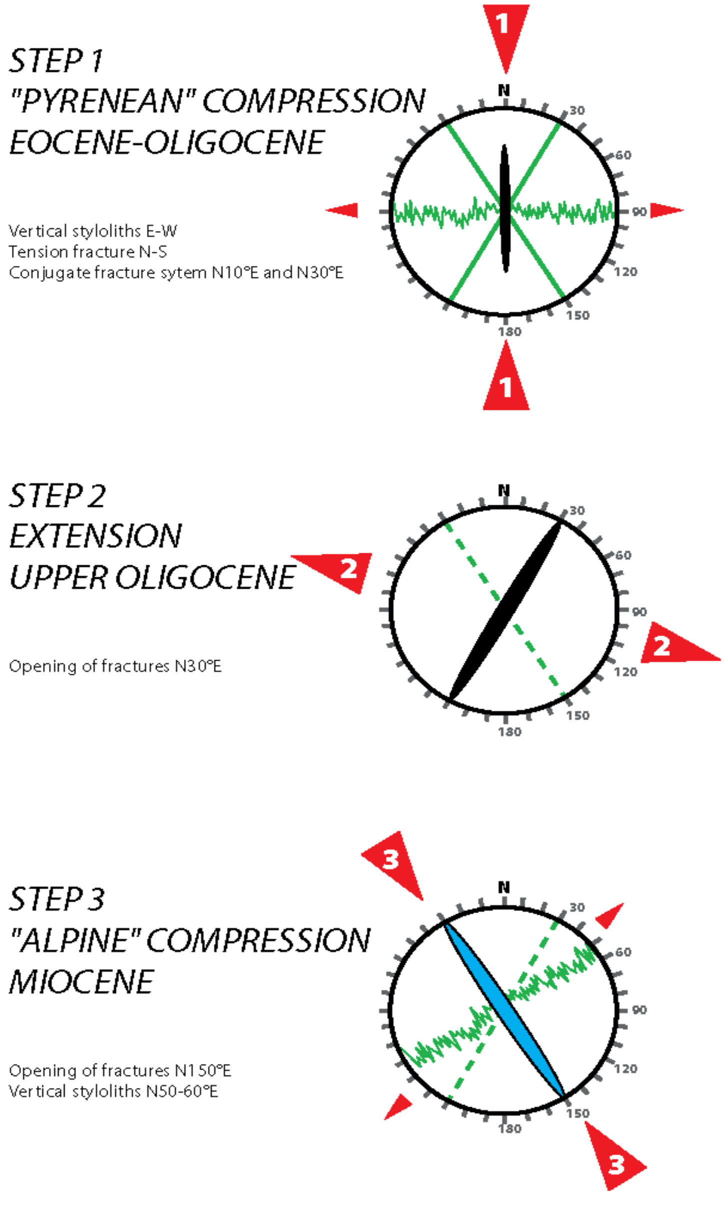


Figure 9: Examples of A) expanded pseudo-parasequences, B) shortened pseudo-parasequences, and C) eroded pseudo-parasequences. For each row, column 1) is an oolitic facies, 2) a mixed oobioclastic facies and 3) a bioclastic facies. The resulting distribution of cements and residual porosity is indicated by the colored stripes. Key: 1- ooids, 2- bioclasts, 3- marl, 4- early cements, 5- intermediate and late calcitic cements, 6- dolomitic cements, 7- residual porosity.



◀ **Figure 10:** Rose diagrams of the tectonic planes in a number of wells from field "X" (east of Paris) scaled with respect to fracture frequency. Key: open fractures (pink), calcite-filled fractures (blue), striated fractures - slickensides - (red), and tectonic stylolites (green). Well locations of this set have been modified to honor confidentiality of the data.

▶ **Figure 11:** Chronology of deformation during the Cenozoic era that affected mid-Jurassic strata in the Paris basin, summarized here as a succession of three phases of tectonism (with red arrows indicating the orientation of the maximum stresses).



In the examples illustrated, a major portion of the heterogeneity in reservoir properties may be attributed to their sedimentary heritage, that is to subtle sedimentologic variations (texture, nature of the elements involved, granulometry, bioturbation, *etc.*), themselves directly controlled by sedimentary dynamics. Diagenetic phenomena, and more specifically cementation, are very often only a superimposition on the original sedimentary structure (its "heritage") and to a certain degree are predictable.

While studying oolitic reservoirs of the same age in the Paris Basin (50 to 80 km southeast of Paris) CUSSEY and FRIEDMAN (1977) conclude that "the patterns responsible for the presence or absence of porosity are related to pressure solution with its attendant reduction of porosity and generation of cement which occludes pores elsewhere in non-compacted ooids, and the position of a paleo-water table in the original depositional environment". By contrast we found that the distribution of porosity results mainly from a "heritage" of depositional facies (primary and early parameter) and that the contribution, either positive or negative, of diagenesis (a set of secondary and late parameters) on porosity is merely a "by-product" of the original sedimentary facies (Fig. 9).

Record of tectonic events

Tectonic interpretation

In all of the wells strata of Dogger age are more or less strongly intersected by tectonic planes. The most remarkable point is that everywhere the orientation of the resulting fractures and fissures is in two major directions: N30°E and N150°E. These two directional trends form conjugate systems that differ in number and character.

In field "X", east of Paris, open fractures trending N150°E are the more numerous (Fig. 10 , pink). Calcite-filled fissures are less consistent in direction, but a N30°E trend predominates (Fig. 10 , blue); they are rare in

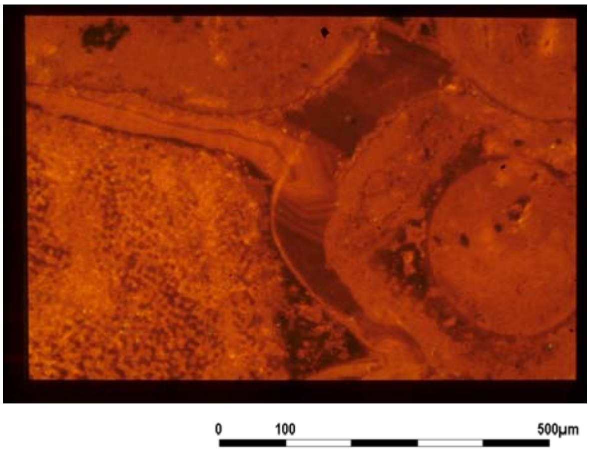


Figure 12: Fragment of the cortex of an ooid with: on its outer side, a thin fringing cement the last phase of which is orange (intermediate) and on its inner side, an orange poecilitic cement (also intermediate) in which the two marker brown zones are recognizable.
(Ref.: 205440X10) (well "X", field "X", east of Paris)

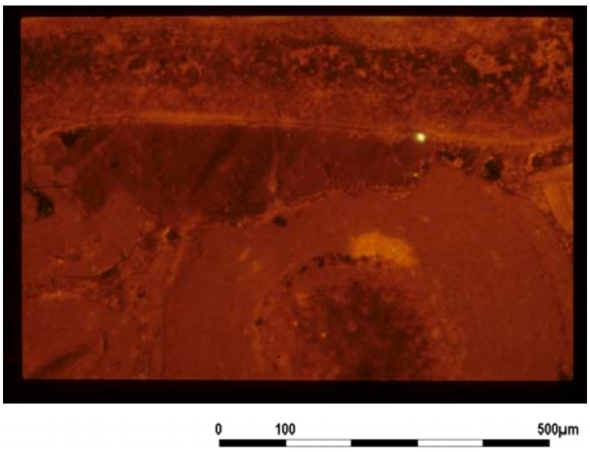


Figure 13: Pressure-solution type contact between an ooid and a poecilitic cement dominantly brown in color (late phase of cementation).
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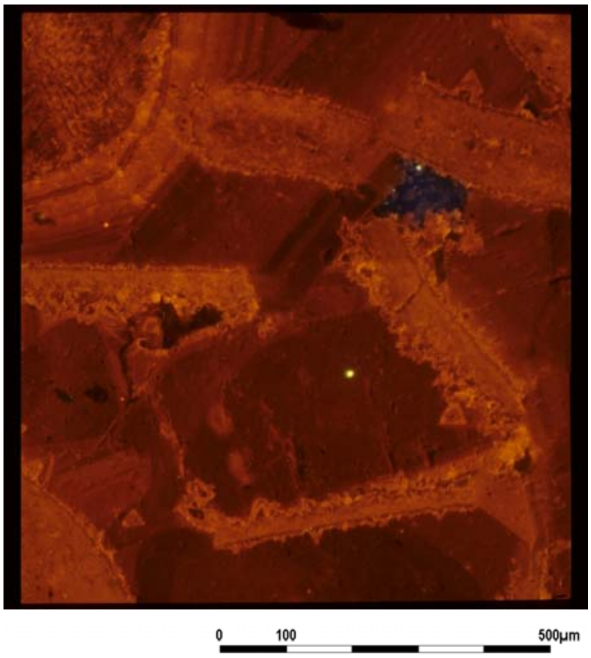


Figure 14: Bioclast bounded by predominantly brown poecilitic crystals (late phase of cementation). (Ref.: 205440X10) (well "X", field "X", east of Paris)

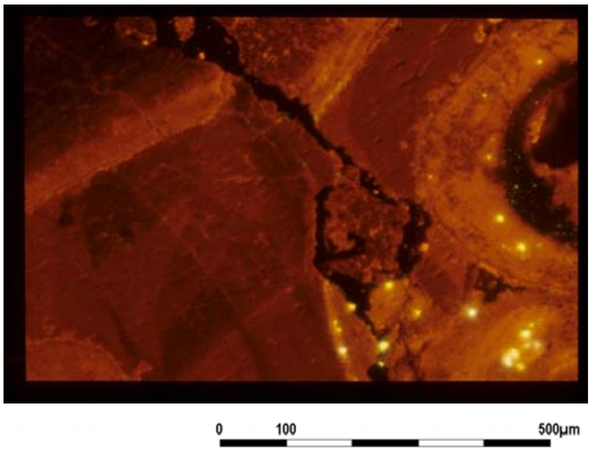


Figure 15: Tectonic stylolites cutting predominantly brown (late phase of cementation) poecilitic cements. (Ref.: 205610X10) (well "X", field "X", east of Paris)

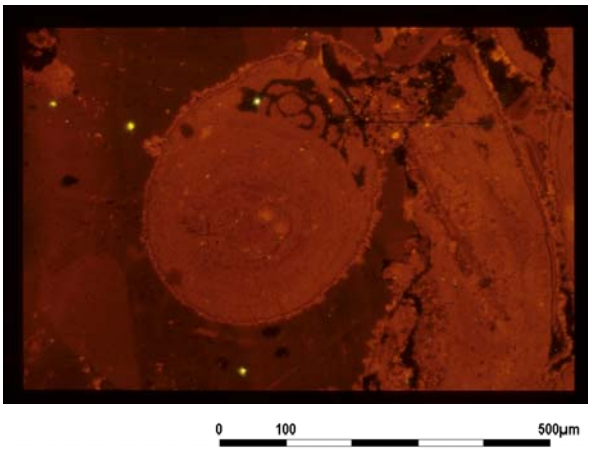


Figure 16: Tectonic stylolites cutting predominantly brown (late phase of cementation) poecilitic cements. (Ref.: 205670X10) (well "X", field "X", east of Paris)

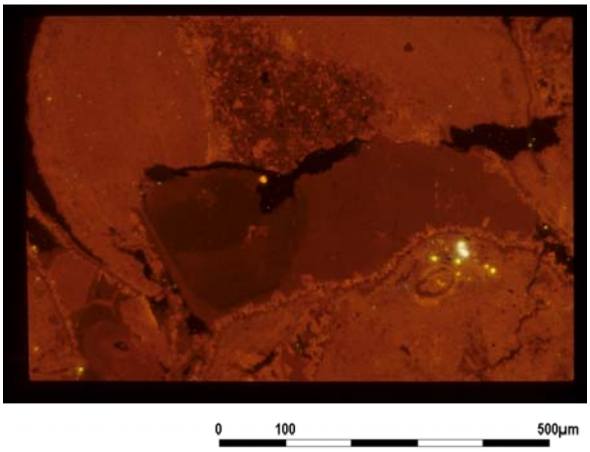


Figure 17: Tectonic stylolites cutting predominantly brown (late phase of cementation) poecilitic cements. (Ref.: 206280X10) (well "X", field "X", east of Paris)

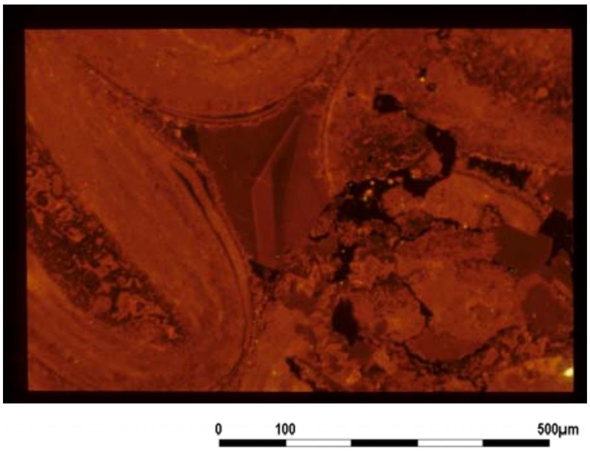


Figure 18: Tectonic stylolites cutting predominantly brown (late phase of cementation) poecilitic cements. (Ref.: 205850X10) (well "X", field "X", east of Paris)

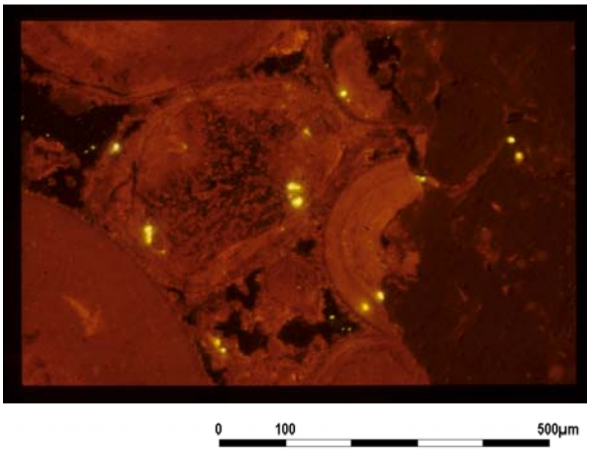


Figure 19: Calcite "veins" filled by predominantly brown (late phase of cementation) poecilitic cements. (Ref.: 205540X10) (well "X", field "X", east of Paris)

the area studied. Striated fractures (micro-faults) are infrequent and present in only a few wells (Fig. 10 , red); their orientation is like that of the open fractures. A synthetic stereo-gram of the slickensides shows that the move-ment was left lateral. Tectonic stress was perpendicular to the fault plane and was probably due to secondary reactivation of the older fractures. The tectonic stylolites (Fig. 10 , green) have two main directions: EW and WNW-ESE, which indicate that stress was applied from NS and SSE-NNW directions.

Relative timing

Structural and kinematic analyses lead us to propose a chronology of tectonic events in 3 steps (Fig. 11):

Step 1: A first compression in a N-S direction caused the following tectonic events :

a) stresses slow and diffuse involving :

- dissolution of tectonic stylolites with hori-zontal dissolution teeth oriented parallel to the main N-S stress.
- opening of calcite-filled fractures in a direc-tion parallel to the main N-S stress

b) another major event:

- the appearance of conjugate fracture sys-tems trending N30°E and N150°E.

Associated with these fractures, are some conjugate strike slip movements, sinistral on the N30°E planes and dextral on the N150°E planes. These movements are not clearly distin-guishable due to secondary and later reacti-vation.

Step 2: A possible extension event with E-W to WNW-ESE directions reactivates the existing fractures which are then partially filled with calcite. Filling is generally more comprehensive in the fissures of the N30°E family which are more nearly perpendicular to the WNW-ESE direction of extension.

Step 3: A SSE-NNW directed compression (still active) affects all the features developed by steps 1 and 2. Some new features are crea-ted and the others may be reactivated:

- tectonic stylolites with horizontal teeth oriented SSE-NNW paralleling the main stress appear;
- fractures and fissures trending N30°E and thus perpendicular to the main new stress must tend to close;
- the N150°E trending fractures should open more or be affected by strike slip move-ment for they parallel to the main stress. In fact, many of the fractures in N150°E tren-ding fractures are partially filled which in any case helps to keep them open.

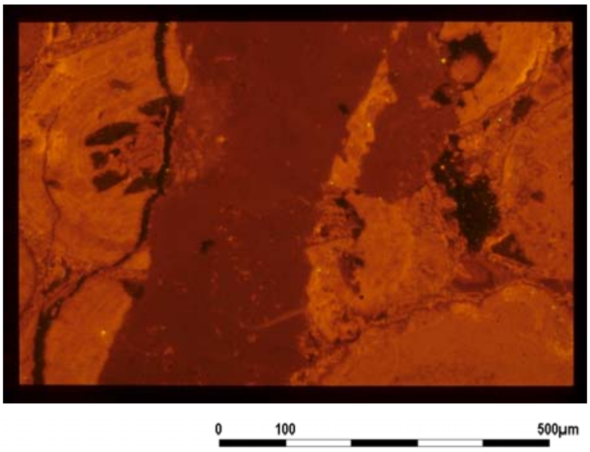


Figure 20: Calcite "veins" filled by predominantly brown (late phase of cementation) poecilitic cements. (Ref.: 205640X10) (well "X", field "X", east of Paris)

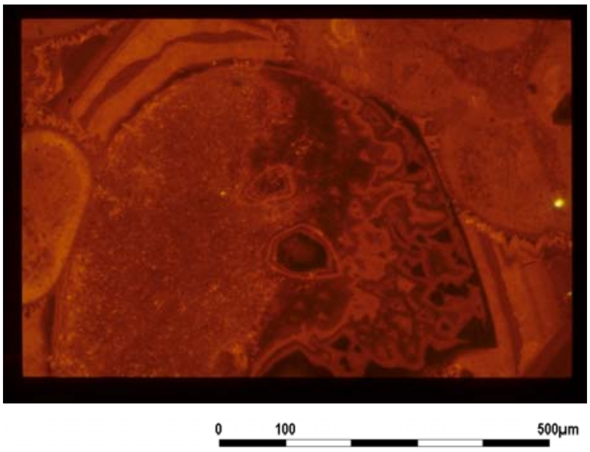


Figure 21: Brown, light brown, orange, brown zoned and black (non-luminescent), cauliflower-like, early phases of cementation, followed by intermediate phases: orange zoned with light brown.
(Ref.: 185795X10) (well "X", field "X", east of Paris)

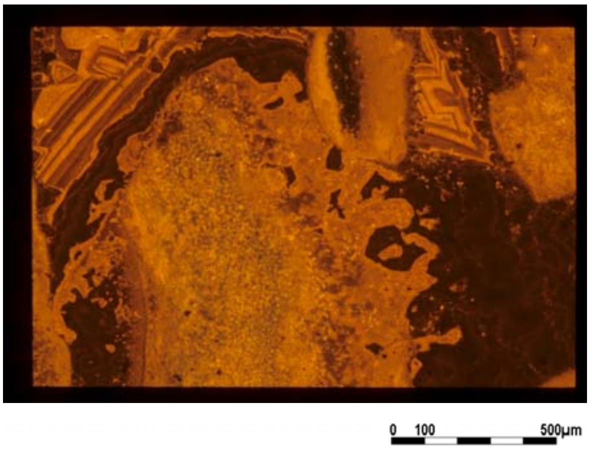


Figure 22: Yellow and dark brown to black (non-luminescent), cauliflower-like, early phases of cementation, followed by intermediate phases with almost linear zone boundaries: light brown zoned with orange.
(Ref.: 2.00X5) (well "S", field "S", east of Paris)

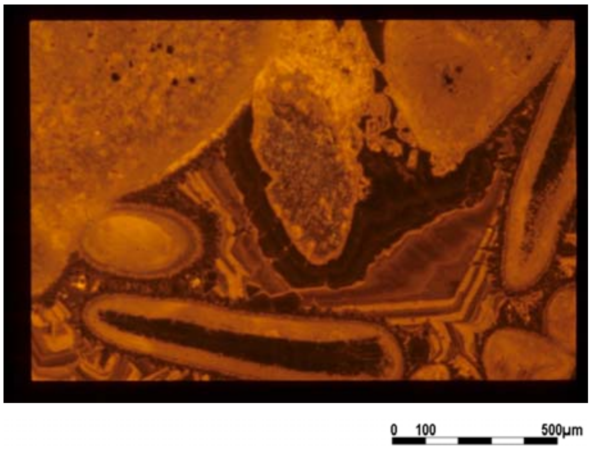


Figure 23: Thin yellow, thick dark brown to black (non-luminescent), cauliflower-like, early phases of cementation, followed by intermediate phases with almost linear zone boundaries: light brown zoned with orange and brown zoned with dark brown.
(Ref.: 2.30x5) (well "S", field "S", east of Paris)

In this N150°E direction of stress, existing fractures show a secondary reactivation by the presence of sinistral strike slip movements as indicated by slicolites. The movement is slow and the amplitude of displacement is related generally to the amount of material that has been dissolved.

Possible dating of events

The analyses made on these cores give only a relative general chronology of the succession of deformations. But here we attempt to relate these events to some existing dated tectonic phases in the Paris Basin (unpublished Corias reports; OBERT *et alii*, 1997; LACOMBE & OBERT, 2000). The three steps of deformation derived from the analysis of the cores may well be related to three recognized tectonic events, as follows:

- Step 1 = "Pyrenean" compression: Middle Eocene-Oligocene
- Step 2 = extension: Late Oligocene (COULON & FRIZON de LAMOTTE, 1988; COULON, 1992)
- Step 3 = "Alpine" compression: Miocene

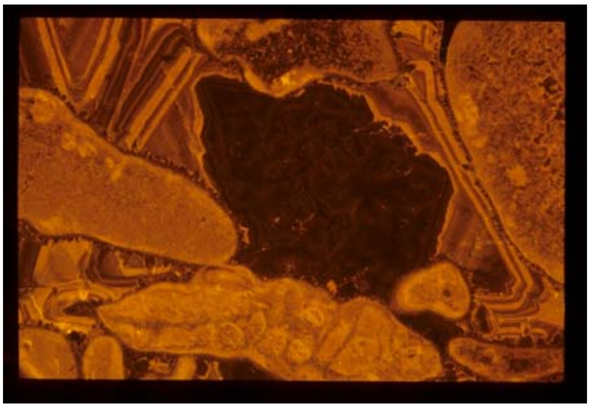
Current stress is about the same as that which prevailed during Miocene times.

Relation to chronology of field "X"

1. Material used

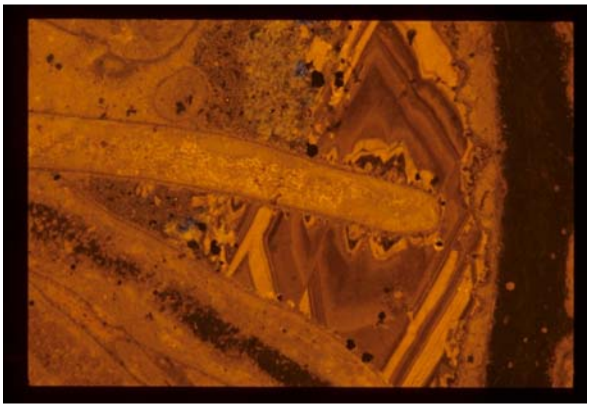
In the area studied (field "X", east of Paris), the upper part of the unit of concentric ooids is characterized by the stacking, even imbrication, of asymmetric bodies of "sand-wave" type or hydraulic dunes, that is, structures that migrated in a south-southeasterly (SSE) direction. Sedimentary dips taken at argillo-organic surfaces (stylolitoids) or at textural changes range between 10° and 20°. The granular facies characteristic of the upper part of this unit are predominantly oolitic and secondarily bioclastic; their textures are commonly grainstone (ooids) and more rarely floatstone (large bioclasts) with a grainstone matrix of ooids and bioclasts. A core (well "X", field "X", east of Paris) was taken in the upper part of the stratigraphic unit of the "Dalle Nacrée", the one characterized by concentric ooids that embraces the upper flow-unit ("R2") of reservoir engineers. In this core are a number of sedimentary laminations, 5 stylolites obviously related to tectonics (perpendicular to the stratification), 2 calcite-filled "veins" and 14 fractures.

Once recognized, the succession of color stages (Fig. 8) makes it possible to relate them to some of the events that occurred during the geologic history of the reservoirs.



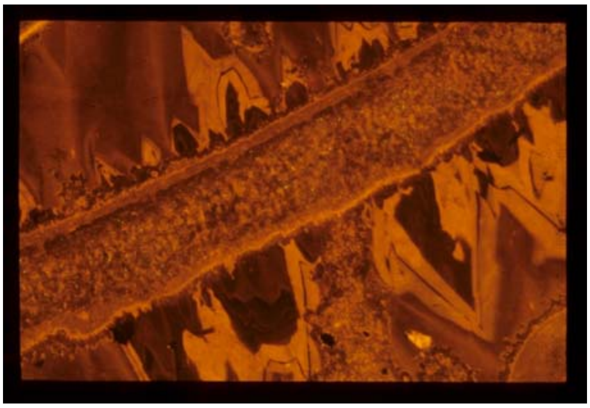
0 100 500µm

Figure 24: Dark brown to black (non-luminescent), cauliflower-like, early phase of cementation, followed by intermediate phases with almost linear zone boundaries: light brown zoned with orange and brown zoned with dark brown.
(Ref.: 2.17X5) (well "S", field "S", east of Paris)



0 100 500µm

Figure 25: The zones in the rim cement of the echinoderm fragment have a zig-zag outline due to an irregular, interrupted micritic encrustation of the echinoderm remain. The following succession is: dark brown to black (non-luminescent), orange zoned with brown, brown to light brown that represent discrete phases of cementation.
(Ref.: 8.16x5) (well "S", field "S", east of Paris)



0 100 500µm

Figure 26: The zones in the rim cement of the echinoderm fragment have a zig-zag outline due to an irregular, interrupted micritic encrustation of the echinoderm remain. The following succession is: dark brown to black (non-luminescent), orange zoned with brown, brown to light brown that represent discrete phases of cementation.
(Ref.: 2.06x10) (well "S", field "S", east of Paris)

2. Tectonic events

Certain tectonic events (fissures and tectonic stylolites) can be calibrated with the relative chronology given by the succession of cathodoluminescence color stages (Fig. 8). Thus:

- Two "calcite veins" are filled with poecilitic cements, dominantly brown in color (Figs. 19-20). Consequently this last step in calcitic cementation occurred after (or during) the formation of these fissures. One may infer a relationship between this fracturing and this calcitic cementation, mostly brown under cathodoluminescence. The arrival of another mineralizing fluid discrete from that of the preceding step (cementation predominantly orange under cathodoluminescence) was possibly favored by this fracturing.
- Several tectonic stylolites cut brown poecilitic cements (Figs. 15-18). This last step in calcitic cementation thus occurred before (or during) the formation of these stylolites.
- Open fractures have not been filled by calcite cements.

Up to this point we have only a relative chronology: if we insert structural information we can date these events:

- The two "calcite veins" filled by dominantly brown poecilitic cements are related to northeasterly oriented fractures (N20°E) attributed to an Oligocene extensional phase (Alsace, Bresse, Limagne and Loire grabens);
- The tectonic stylolites with a disposition toward brown poecilitic cements trend N30°-N50°E. They are attributed to a Miocene compressional phase (rise of Jura and Morvan ranges).

- The open fractures are assumed to be related to fractures trending N150°-170°E also attributed to this last phase of compression.

3. Rearrangement of grains

During burial, grains are rearranged in zones where the sediment was poorly sorted and/or into zones where there was little or no early cementation. These rearrangements are shown by burst grains (a part of intergranular porosity is thus changed to "intragranular"), by inter-penetration of grains, and sometimes by pressure-solution contacts with their cements, by solution seams (stylolitoids), or by genuine, non-tectonic stylolites. Thus in addition to tectonic events, the timing of re-arrangement of grains can be calibrated with the relative chronology of cementation phases:

- A fragment of oolitic cortex (Fig. 12) has on its outer side a weakly developed bordering cement of which the last phase is orange, and on its inner side a poecilitic, dominantly orange cement in which the two brown marker zones exist The break-up of the ooid must have occurred relatively early during the second stage of cementation.
- The fragments of a bioclast (Fig. 14) are bounded by poecilitic crystals of a dominantly brown tint. This grain was probably broken (relatively early) during the the last stage of calcitic cementation.
- A "pressure-solution" contact between an ooid and a predominantly brown poecilitic cement (Fig. 13) suggests that this process took place either during or after the final step of calcitic cementation.

The calcitic cements studied do not contain inclusions of fluid hydrocarbons; these fluids probably reached the reservoir after the last phase of calcitic cementation. As the source rocks possibly reached thermal maturity by the end of the Cretaceous times (unpublished Total reports; Duval, 1991; Hanot & Obert, 1992; Burrus, 1997), it is highly probable that oil and gas migrated from deeper reservoirs in Miocene times (thus it was a dismigration), during Alpine compression caused fracturing and faulting that served as pathways for migration into a newly created generation of structural traps.

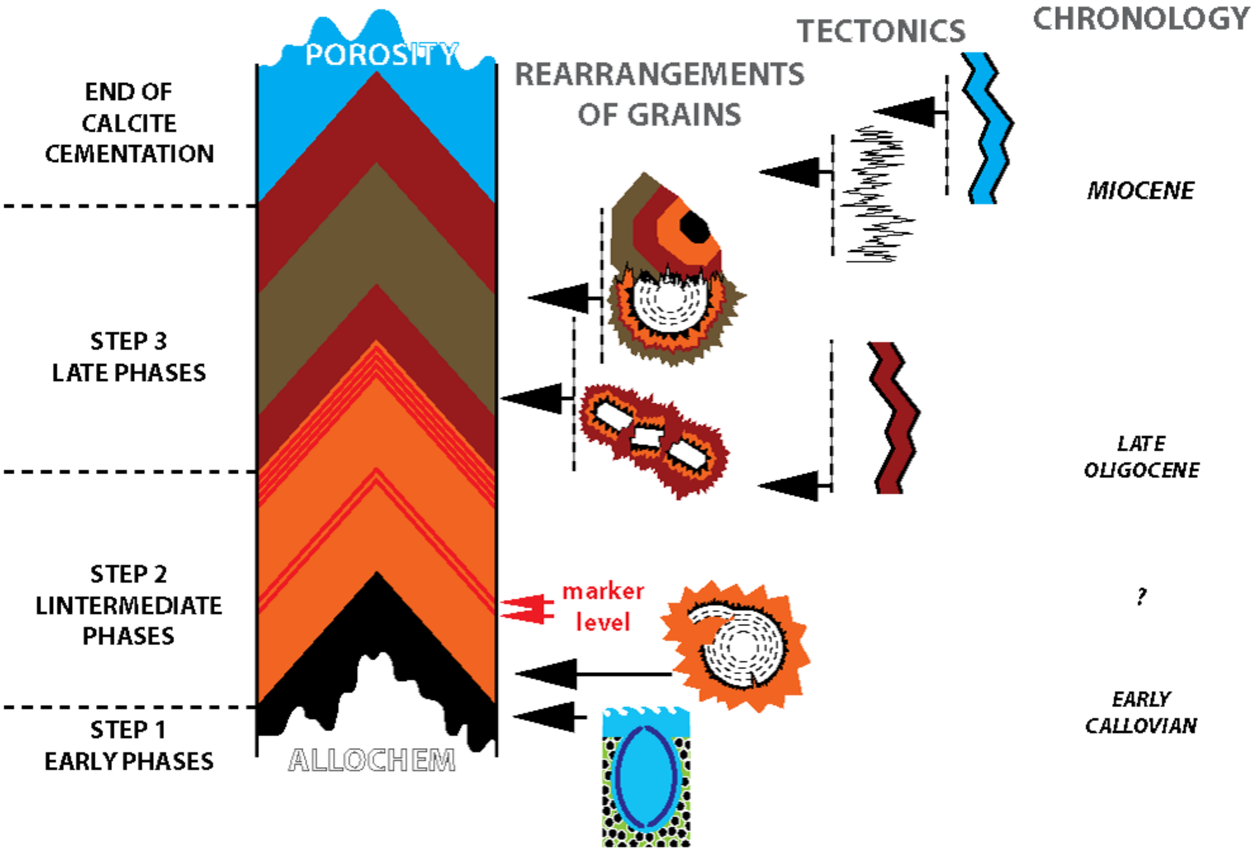


Figure 27: Dating of a paragenetic sequence using the successive phases of cementation over time, cementation as related to grain rearrangement, and the development of tectonic fractures and stylolites.

Conclusions

Effective porosity in the oolitic reservoirs of Villeperdue (Granier, 1993, *et sequitur*) or of "S" and "X" fields (unpublished Total reports) is essentially residual porosity, that is the porosity remaining in the intergranular spaces after their partial filling by cement. Here there is no evidence whatsoever that "sea level dropped and the ooid shoals emerged following their accumulation" and that consequently a contemporaneous cementation occurred "in the phreatic zone below the ground-water (*i.e.*, fresh-water) table" as stated by CUSSEY and FRIEDMAN (1977) about the oolitic reservoirs (possibly Bathonian in age) of the Marolles field, 40 km south of Paris.

The analysis of calcitic cements by cathodoluminescence furnished a general indication of the following paragenetic sequence (Fig. 27):

- Early phases of marine cementation (Early Callovian),
- Intermediate phases of cementation, predominantly orange under cathodoluminescence (Callovian to Middle Eocene),
- Opening of fracture trending N20°E, possibly related to Pyrenean compression (Middle Eocene-Oligocene) with a "recharge" of the aquifer (the cathodoluminescence change in color from orange to brown is presumably related to the change in water chemistry),
- Late phases of cementation, predominantly brown under cathodoluminescence, that filled the fractures trending N20°E, that is the "calcite veins" (Oligocene),
- Tectonic stylolites trending N30°-50°E and open fractures trending N150°-170°E, possibly related to Alpine compression (Miocene),
- Addition of hydrocarbons to the reservoir (Miocene to Recent), probably aided by the Miocene fracturing,
- Continuance of cementation below the oil-water contact.

Most of these findings, in particular the timing of the events, are contrary to those reported by ANDRÉ (2003) and by VINCENT *et alii* (2007) about Oxfordian and Kimmeridgian carbonates of the Paris Basin. As this succession of events is calibrated on the well-defined regional tectonic calendar (unpublished Corias reports; OBERT *et alii*, 1997; LACOMBE & OBERT, 2000), it offers a new perspective for the exploration of and production from the Middle Jurassic oolitic reservoirs of the Paris Basin: we assume that hydrocarbons possibly dismigrated from disrupted EW trending structures of Pyrenean age so the best prospects for these new finds should be SW-NW trending structures of Alpine age, possibly in combination with sedimentologic, diagenetic or stratigraphic closures (as in the Villeperdue oil field: see ARBIN & EURIAT, 1989; DUVAL, 1991; GRANIER, 1993, *et sequitur*).

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