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Synthesis of recent stratigraphic data on Bathonian to Oxfordian deposits of the eastern Paris basin

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Key-words. – Eastern France, Paris basin, Stratigraphy, Biostratigraphy, Middle Jurassic, Upper Jurassic, Palaeogeography, Platform carbonates, Clay mineralogy, Bentonite

Abstract. – Data acquired over the last decade on the eastern Paris basin, largely as a result of research carried out by the French national radioactive waste management agency (Andra) with the objective of evaluating the feasibility of an underground waste disposal facility, is the basis for proposing a very accurate bio-chronostratigraphic sequence for the studied interval (Bathonian to Oxfordian), and especially within the claystone layer considered as a potential repository host formation. Data obtained at the local scale regarding both the claystone layer and the under- and over-lying platform carbonates have been integrated into the regional framework by correlating all available borehole data, reinterpreted in accordance with the new findings made available by the Andra boreholes and specific outcrop studies.

The upper surface of the lower Callovian carbonate platform is relatively isochronous at the scale of the Meuse/Haute-Marne (M/HM) sector (several hundred km^2) and marked by a discontinuity. The overlying upper Callovian to lower Oxfordian clays have been deposited according to a north to south overall progradational trend, as evidenced by detailed well log correlations at the regional scale. The downlap surface is marked by condensed deposits (iron oolites) that cover a longer stratigraphic interval to the south (Burgundy swell) than to the north. The Andra M/HM underground research laboratory is positioned in the uppermost part of the descending volume of the clay wedge. Biostratigraphy has been refined on the basis of ammonites found both in nearby outcrops and in the Andra boreholes. Regional correlations including these new biostratigraphic data, as well as other markers observed in well log data, show a rapid change in clay mineralogical characteristics within the Lower Oxfordian, and an altered ash layer (bentonite) in the upper part of the clay formation (Plicatilis Zone, middle Oxfordian).

The overlying middle to upper Oxfordian carbonate platform has been extensively investigated. The Middle Oxfordian carbonates are divided into two parts. The lower eastern part is made up of alternating coral-rich units and oncolithic packstones in which corals are sparse or completely lacking, both facies representing depositional sequences in which the coral-rich units represent relatively moderate flooding. This lower part thins out towards the NE (i.e. the outcrops of the "côtes de Meuse" where emersion surfaces occur, as well as the low-lying oncolithic facies found in the Andra boreholes wells, are supposed to come from crinoïdal limestone: "Entroquite"), especially in the transgressive swash bars anchored on previously exposed high-lying reefs. The upper part of the middle Oxfordian carbonates is mostly a lagoonal facies that was isolated from the open sea in the south-west by a coral-bearing, oncolithic/oolithic barrier facies. A moderate flooding, probably associated with a climate cooling responsible for a temporary decrease in carbonate productivity, occurred at the beginning of the late Oxfordian, creating a regional marlstone seal over the underlying carbonates. Overlying upper Oxfordian platform carbonates are made up of three oolithic depositional sequences. Regional facies maps have been reconstructed from outcrops and borehole log correlations.

These middle to upper Oxfordian platform carbonates have been affected by post-depositional, irregularly distributed, degradational diagenesis that converted all of the different facies types into a porous secondary chalk. The regional extent of the most transformed layers, as well as the actual diagenetic mechanisms, still need to be studied.

Some changes in the location of maximum subsidence occurred throughout this time interval. Some of the faults of the present-day network may have undergone temporary synsedimentary movement, resulting in small thickness changes and/or the position of some facies boundaries (Metz faults, for instance), but there is no clear evidence of a syn-depositional movement of the major Vittel fault.

Synthèse des données stratigraphiques récentes sur les formations bathoniennes à oxfordiennes de l'Est du bassin de Paris

Mots-clés. – Est de la France, Bassin de Paris, Stratigraphie, Biostratigraphie, Jurassique moyen, Jurassique supérieur, Paléogéographie, Plate-forme carbonatée, Argilites, Bentonite.

Résumé. – Les données géologiques collectées depuis le début des travaux de l'Andra sur le secteur situé dans le sud du département de la Meuse et le nord du département de la Haute-Marne permettent de proposer un découpage bio-chronostratigraphique très fin de l'intervalle Bathonien à Oxfordien, basé sur un grand nombre de techniques, notamment dans le Callovien – Oxfordien argileux.

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Celles-ci révèlent une isochronie relative du toit du Dogger calcaire, avec arrêt de sédimentation dans tout le secteur Meuse/Haute-Marne. La reprise de la sédimentation argileuse au Callovien inférieur/moyen-Oxfordien inférieur est en revanche diachrone, depuis l'Ardenne jusqu'à la plate-forme bourguignonne alors ennoyée. Ce diachronisme s'explique par le remplissage en progradation du nord vers le sud d'une zone subsidente centrée sur l'Est du bassin de Paris, et donc le pincement aval du prisme argileux qui passe vers le sud, sur des zones hautes, à des dépôts condensés à oolithes ferrugineuses.

L'ensemble des éléments de corrélation disponibles sur le secteur, *i.e.* une approche biostratigraphique précise basée sur la reconnaissance de zones, sous-zones, horizons d'ammonites permettant de fixer les limites d'étages et de sous-étages, la reconnaissance de surfaces diagraphiques isochrones, l'utilisation d'un niveau de bentonite repère, l'évolution des cortèges argileux, permet de démontrer l'absence de lacunes majeures dans la pile sédimentaire, n'excluant toutefois pas des hiatus de très courte durée ou niveaux de condensation localisés. Ces différents critères stratigraphiques à valeur corrélative traduisent une cohérence d'ensemble dans la disposition géométrique des différents corps sédimentaires et l'homogénéité de la couche argileuse.

L'étude minéralogique des argilites met en évidence un rapide changement dans la nature des interstratifiés illite-smectite, associé à la disparition de la kaolinite qui marque la surface d'inondation maximale du grand cycle transgressif/régressif bathonien – oxfordien dont les argilites médianes représentent le faciès d'ennoyage marin.

La mise en place des plates-formes carbonatées suivantes, au cours de l'Oxfordien moyen – supérieur, est également légèrement diachrone d'est en ouest et du nord au sud, pour la même cause de progradation générale dans ces directions. L'épisode carbonaté de l'Oxfordien moyen débute vers la base de la Zone à Transversarium et se termine au sommet du sous-étage. Cette première plate-forme carbonatée est séparée de celles de l'Oxfordien supérieur (trois épisodes oolithiques) par une couche argileuse généralisée mais assez mince, mise en place au début de l'Oxfordien supérieur. Le style de ces plates-formes change au cours du temps, passant de l'état de rampe faiblement pentée vers le sud à celui de plate-forme à la fois aggradante et légèrement progradante. Un léger mouvement de bascule vers l'Ardenne accompagne l'approfondissement modéré constaté à la base de l'Oxfordien supérieur; il accélère par contrecoup la progradation de la plate-forme carbonatée vers le sud et provoque une hétérogénéité faciologique en direction de l'Ardenne avec des intercalations gréseuses.

Sauf pour le faisceau de failles de Metz, qui semble avoir contrôlé la répartition des faciès au nord-est, l'influence sur la sédimentation des principaux accidents tectoniques (failles de la Marne, faille de Vittel, etc.), souvent suggérée, n'est pas très évidente au vu des cartes de faciès et d'isopaches publiées. Tout au plus, des coïncidences temporaires suggèrent que certains accidents ont pu induire un différentiel de subsidence ayant pu contrôler quelques paramètres de la sédimentation (profondeurs de dépôt, faciès, épaisseurs). L'impression dominante est celle d'une assez grande stabilité au cours de l'intervalle stratigraphique considéré, les légères différences locales se compensant globalement au cours du temps.

Les carbonates oxfordiens de plate-forme ont subi une diagenèse crayeuse, encore mal étudiée, responsable d'horizons poreux recensés à l'aplomb du village de Bure. La continuité latérale de ces horizons à l'échelle régionale doit encore être prouvée.

INTRODUCTION

The project for the installation of an underground laboratory in the Callovian – Oxfordian claystones of eastern France by the French national radioactive waste management agency (Andra) in order to study the feasibility of a possible radioactive waste disposal, required a detailed investigation, not only of the Callovian – Oxfordian host layer but also of its underlying and overlying limestone formations.

The work, which includes, in particular, detailed geological mapping, partial or fully cored boreholes and seismic reflection (2D and 3D) concerns an area (fig. 1) principally located between:

– the latitude of Saint-Dizier, to the north, and the Vittel fault, to the south,

– the Marne faults (inclusive), to the west, and the western end of the Gondrecourt graben, to the east.

This area, which covers the south of the Meuse district and the north of the Haute-Marne one is referred to as "M/HM sector" afterwards in the document.

The aim here is to summarise all the results of the stratigraphic and sedimentological studies carried out by contractors and university laboratories since the end of the 1990s, both in the M/HM sector and, at a much greater scale, in the eastern part of the Paris basin.

The Paris basin may be described as a extensive basin, the thermal consequence of the Permian extension, which gradually evolves towards a compressive basin, temporarily at first (early Berriasian and latest Aptian), then permanently (latest Turonian – Present day) [Guillocheau *et al.*, 2000a, b]. Its evolution consists of five remarkable stages, which are reminders of major geodynamic events: Scythian/Toarcian, Aalenian/Tithonian, Berriasian/latest Aptian, latest Aptian/latest Turonian, latest Turonian/Present day. Each stage is marked by a reorganisation of the subsidence areas of the basin. Therefore, the Turonian/Present day episode is the consequence of the Africa/Eurasia convergence with the folding (buckling) of the lithosphere under the basin. Several thermal events are superimposed on this evolution [Clauer *et al.*, 1995], at 190 Ma (Pliensbachien), 150 Ma (Oxfordian according to Odin [1994]) or Tithonian, according to Gradstein *et al.* [1994], and Gradstein and Ogg [2004], and 80 Ma (Campanian); they are accompanied by an increase in the subsidence rate.

From a stratigraphic point of view, nine major transgressive/regressive cycles over a time scale of 10 to 45 Ma (second order cycles) may be identified from the Triassic (Scythian) to the Upper Cretaceous (Cenomanian) [Jacquin *et al.,* 1998; Guillocheau *et al.*, 2000a, b; Robin *et al.*, 2000]. The studied stratigraphic interval lies in the

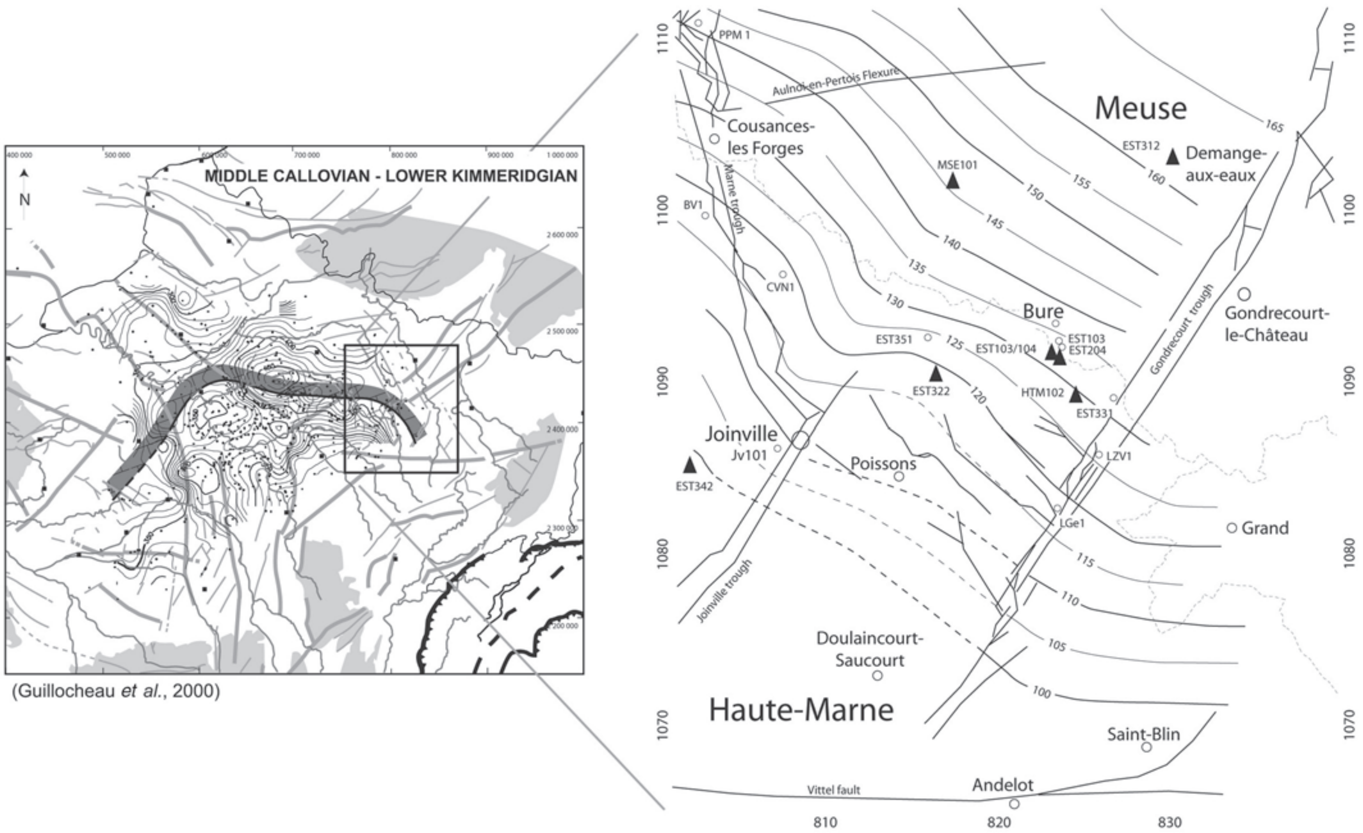

Fig. 1. – Location of the Andra wells used in the Meuse/Haute-Marne (M/HM) area. Isopachs of the Callovian-Oxfordian clay formation in the Meuse/Haute-Marne area. On the left, situation of the study area on an isopach map for the middle Callovian – upper Oxfordian regressive half-cycle at the Paris Basin scale, showing the approximate position of the southern limit of platform carbonates (shaded) for this interval.

Fig. 1. – *Situation des forages de l'Andra utilisés sur le secteur Meuse/Haute-Marne (M/HM). Isopaches de la couche argileuse callovo-oxfordienne. A gauche, situation du secteur Meuse/Haute-Marne sur une carte d'isopaches du demi-cycle régressif Callovien moyen – Oxfordien supérieur à l'échelle du bassin de Paris montrant la position approximative de la bordure de la plate-forme carbonatée oxfordienne (ombrée).*

lower Bathonian cycle (Zigzag zone, Yeovilensis sub-zone) Upper Oxfordian (Bimammatum zone, Hypselocyclum sub-zone), as defined on the outcrop by Jacquin *et al.* [1998]. In the "Folie de Paris" borehole [Guillocheau *et al.,* 2000a, b; Robin *et al.,* 2000], the maximum flooding surface is in the middle Callovian (Jason zone, Jason sub-zone) or in the lower Oxfordian (Mariae zone, Scarburgense sub-zone) according to Jacquin *et al.* [1998]. This second dating is in agreement with the results of the studies carried out on the Bure site [Pellenard *et al.,* 1999].

The Aalenian – Tithonian period is characterised by areas of subsidence running NW-SE, along the Seine and Bray faults. The NE-SW directions are still active in the central part of the basin.

This fundamental reorganisation of the subsidence axes is the result of a major deformation between plates, which affected eastern Europe during the Aalenian period (mid-Cimerian deformations) and appears to have continued during part of the Bajocian period. The maximum period of activity of this event is still unclear in chronostratigraphic terms (limit between the Toarcian/Aalenian period or latest Aalenian). It is contemporary with the thermal doming of the North Sea, which preceded the rifting stage [Underhill and Partington, 1993]. This event accentuates the tendency towards the flexure initiated during the Toarcian period, with truncations and condensed deposits ("Minette of Lorraine").

From the Aalenian to the Tithonian, the importance of tectonic control decreased; the Kimmeridgian (and probably the Tithonian) corresponds to the period during which the subsidence rate is maximum (accommodation: 20 to more than 30 m/Ma) and homogeneous in space (the smallest gradients), whilst the facies are homogeneous throughout the basin (with the exception of the Boulonnais, coastal domain). This rupture took place during the Callovian, period of transition from rift to the passive continental margin in the Tethysian Ligurian domain, and therefore during the transition towards a regime of flexural subsidence of thermal origin.

From the Aalenian to the Tithonian period, the Paris basin was therefore globally part of an extensive system, even if some compressive movements were possible between the Brabant and the Cadomian block during the Aalenian period.

A second diagenetic event affected the basin: it is dated at 150 Ma (Oxfordian for Odin [1994], Tithonian for Gradstein *et al*. [1994], Gradstein and Ogg [2004]). It was a brief event (probably less than 1 Ma) and cooler than that dated at 190 Ma [Clauer *et al*., 1995] which coincided with a further, more intensive period of subsidence. It was also accompanied by paleomagnetic rejuvenation of the southern Vosges Carboniferous series [Edel, 1997].

The Aalenian – Tithonian period corresponds to the formation of large carbonate platforms with different geometries and depositional profiles: platforms of calcarenites and reefs of Bajocian age [Durlet, 1996; Thiry-Bastien, 2002], isolated shoals of oolites in the late Bajocian [Thiry-Bastien, 2002] and the Bathonian [Purser, 1975; 1980; Garcia *et al.*, 1996; Gaumet *et al.*, 1996; Gaumet, 1997], prograding platforms with reefs and carbonate muds in the Oxfordian, aggrading platforms of carbonate muds in the Tithonian.

The subdivisions adopted in the remainder of the document corresponds to the three main lithological units studied: (a) the top of the carbonate formation of the upper Bathonian – lower Callovian located under the Callovian-Oxfordian argillites, (b) the middle Callovian – lower Oxfordian argilites proper and finally, (c) the overlying middle-upper Oxfordian carbonates.

THE UPPER BATHONIAN – LOWER CALLOVIAN CARBONATE PLATFORM

Litho-biochronological data

In the eastern and southeastern parts of the Paris basin (Côte d'Or, Haute-Marne and Meuse), the uppermost Bathonian – lower Callovian sedimentary series *p.p.*, making the substratum of the Callovian-Oxfordian argillaceous formation, is dominated by carbonate platform facies. Different members are identified: Dijon-Corton stone, *Rynchonella* bearing limestones, Ladoix stone, plant bearing limestones, Etrochey limestones [Thierry, 1966; Floquet *et al.*, 1989; Gaumet *et al.*, 1996; Garcia and Dromart, 1997].

These members come from shallow platforms, deposited either in high or low energy environments, with facies mainly dominated by coarse granular, oolitic and/or bioclastic limestones, or finer bioclastic limestones with micritic matrix. The top of each member is often marked by an omission surface, which is occasionally hardened and perforated. In general, such sedimentary discontinuities are sealed by thin (decimetric) marly to argillaceous levels. These are interpreted as maximum flood surfaces, which may be correlated at the scale of the Paris basin, and which generally correspond to characteristic associations of brachiopods [Garcia *et al.,* 1996; Garcia and Dromart, 1997].

The different members defined belong to the "Dalle nacrée" formation *s.l.*, a useful but rather obsolete term [Thierry *et al.*, 1980; Floquet *et al.*, 1989]. Its top, marked by a major discontinuity of regional scale, was the base for the resumption of sedimentation. This resumption is dated locally from the end of the early Callovian (Calloviense zone, Enodatum sub-zone), or more generally from the base of the middle Callovian (Jason zone, Medea sub-zone). It is marked by a very clear lithological change resulting from the deposition of either condensed layers of ferruginous oolites on the Burgundian platform to the south-west [Collin *et al.*, 2005], or oolitic marls with more carbonated, ferruginous seams or mudstones further to the north, as in M/HM sector where the Callovian-Oxfordian argillaceous formation rests directly on the carbonate facies of the "Dalle nacrée".

In M/HM sector, the Andra boreholes HTM102 (Cirfontaines-en-Ornois – Haute-Marne district) and MSE101 (Morley – Meuse district) crossed two limestone units, under the upper discontinuity of the "Dalle nacrée", which is a major feature at the scale of the eastern part of the Paris basin and which here, takes the form of a hardened, perforated surface: an upper unit, made up of oobioclastic granular limestones attributed to the "Dalle nacre"; a lower unit, made up of compact oolitic limestones and, locally, dolomitic limestones ("Chaumont" Comblanchien limestone), partial lateral equivalent of the facies of the summit of the "Comblanchien limestone" formation further to the South, in the Côte d'Or.

In outcrops, the large foraminifer *Orbitammina elliptica* (= *Meyendorffina bathonica auct*. BASSOULET, 1997) is the only dating element, which indicates the upper Bathonian (Retrocostatum zone and Discus zone) of the "Comblanchien limestones". This microfossil was observed in these limestones in thin sections in MSE101 borehole at a depth of 660.23 m [Dromart and Garcia, 1996]; it was not found in HTM102 borehole.

Depending on the sectors, the Bathonian – Callovian limit either coincides with the start of the granular oobioclastic facies, or is found in the lower third. In this case it is surrounded at the base by the datum horizon at *Eudesia multicostata* and *Burmirhynchia elegantula*, which gives scarce ammonites of the uppermost Bathonian (Discus zone, Discus sub-zone) at outcrops, and above by the datum horizon at *Digonella divionensis* and *Lotharingella gremifera* which provides usual ammonites of the lowermost Callovian (Herveyi zone, Terebratus sub-zone) in outcrops.

In the absence of ammonites in the limestone facies, the rare datings obtained in the Andra boreholes are deduced by correlation with the event-stratigraphy and biostratigraphic scales established in the eastern part of the Paris basin and supported by palynology and brachiopods [Jan du Chêne, 1995, 1996a-b; Andra, 1998]. They enabled the Bathonian – Callovian limit to be placed at 482.15 m in HTM102 borehole and 658 m in MSE101 borehole. In both cases, this limit coincides with the contact between the "Comblanchien limestones" and the oobioclastic limestones of the "Dalle nacrée".

In comparison with the outcrops of the adjacent regions, the oobioclastic facies of the boreholes contain in their lower third brachiopods of the *Digonella divionensis* – *Lotharingella gremifera* and *Ornithella sp.* – *Lotharingella leedsi* associations of the lowermost Callovian (Macrocephalus zone). In the upper two thirds, depending on the area, the *Kallirhynchia* – *Ornithella sp*. associations of brachiopods confirm the presence of the Koenigi sub-zone, the Sub-Calloviense zone and the Calloviense zone of the lower Callovian [Dromart and Garcia, 1996].

Despite lateral variations of facies, reductions in thickness and condensations of lithological units, enough dating elements have been found to localise accurately the lower Callovian – middle Callovian boundary, which corresponds to the limit between the Calloviense zone and the Jason zone [Thierry *et al.*, 1997].

Depending on the outcrops, it may be placed: (1) slightly above the top of the granular oobioclastic facies, within the base of the overlying limestone-clay deposits (Saint-Blin, approximately 20 km to the SSE of the Bure laboratory site), (2) or coincidental with the perforated summit surface of the oobioclastic facies (the most common situation due to the absence of ammonites both in the limestone facies and at the base of the overlying clays), (3) or a few decimetres under the perforated surface of the summit of these limestones (Marault, near Chaumont-Bologne, to the SSW).

Thus, further SSE, at Humbertville near Saint-Blin [Marchand and Thierry, 1977], the perforated surface at top of the "Dogger" oobioclastic limestone is older. It is dated from the Calloviense sub-zone, base of the Calloviense zone of the lower Callovian. The lower Callovian-middle Callovian limit is placed above the perforated surface, on the top of a thin layer of argillaceous, ferruginous oolitic limestones dated from the Enodatum sub-zone, at the summit of the Calloviense zone.

Still further to the SSW, at Marault, the last beds of the oobioclastic facies are dated directly by ammonites of the Sub-Calloviense zone.

In the boreholes, where ammonitic fauna is totally absent in the granular oobioclastic facies and quite scarce at the base of the argillaceous deposits, the lower middle Callovian limit was considered coincidental with the top of the "Dogger" oobioclastic limestone (HTM102, 472.20 m; MSE101, 650.43 m); it therefore coincided with the start of argillaceous sedimentation ("Woëvre clays").

Amplitude of variations in sea level. Sedimentological and diagenetic approach

Since the work of Purser [1975, 1980] and especially since the end of the 1980s, faciological, diagenetic and stratonomic changes, indicative of bathymetric variations have been found in Bathonian-Callovian carbonate deposits of the eastern part of the Paris basin. Sedimentary cycles, comparable to third or fourth sequences *sensu* Vail *et al.* [1991], have been described in particular on the Burgundy platform in outcrops and boreholes [Floquet *et al.,* 1989; Javaux, 1992; Garcia, 1993; Garcia *et al.,* 1996; Garcia and Dromart, 1997; Gaumet *et al.,* 1996; Gaumet, 1997; Collin, 2000]. These sequences, which may occasionally be correlated with the sequential charts of European basins [Hardenbol *et al.*, 1998], have been attributed to eustatic, tectonic, or climatic processes, or even to simple, local and autocyclic variations of the production rate of carbonates. Similarly, the amplitudes of variations in sea level associated with such sequences have been estimated in several ways. Depending on the authors, reduction in accommodation has been attributed to lowstand prograding wedges or shelf margin wedges *sensu* Vail *et al.* [1991]. In the first case, it was assumed that sea level drops of an amplitude from several metres to several tens of metres result in the emersion of a large part of the platform. In the second case, very small or no reductions in sea level (without allocyclical emersion of the platform), were suspected.

Investigations have been carried out recently in order to identify and quantify possible drops in sea level in the Bathonian – Callovian series. Based on the study of about twenty outcrops throughout the districts of the Saône-et-Loire, the Côte d'Or, the Nièvre and the Haute-Marne, they focused on the nature and extension of the sedimentary or diagenetic evidences of the Burgundy platform emersion.

On completion of this investigation, it appeared that no emersion with corresponding introduction of meteoric water occurred in the area during the Bathonian – Callovian period. Some cavities located under discontinuities have occasionally been attributed to paleo-karsts. In fact, they are due either to biological cavings or to the precocious dissolution of fully aragonitic bioclasts (corals, gasteropods, dasycladal algae, etc.). During the Jurassic period, such dissolution of aragonite could have occurred in sea-water, under burial conditions ranging from shallow to nil [Palmer *et al.,* 1988]. This process can be associated with the absence of aragonitic cements during the same period. It was probably due to high partial pressures of CO_2, with a low Mg/Ca ratio in the sea-water, and/or to the bacterial decay of organic matter [Sanders, 2003]. In this case, the petrographic and chemical analyses carried out on the filling of cavities did not reveal any cement or internal sediments of meteoric origin. Calcite cements with low magnesium contents, in the form of scalenohedral or syntaxial overgrowths are occasionally contemporary with the sedimentary disruptions associated with such discontinuities [Javaux, 1992; Collin, 2000]. In view of their low magnesium content, sparites of this type could be formed in contemporary emersion fresh water aquifers. Nevertheless, the few isotopic analyses carried out on these early cements, using the IMS 70 microprobe of the CRPG laboratory (Nancy) [values of $\delta^{18}O$ between –1.8 and + 0.2% PD], indicate precipitation from sea water, rather than from meteoritic or mixed waters.

However, sedimentological (bird's eyes, dessiccation casts, etc.) or diagenetic (microstalactitic and meniscus cements initially formed by magnesian calcite) emersion indices have been reported, in particular, in Bathonian carbonates [Purser, 1980; Javaux, 1992]. All may have been formed during brief periods of emersion in intertidal to supratidal environments. They are not evidence of long-lasting drops in relative sea level.

Therefore, the sequence boundaries which have been described for the Burgundian platform [Floquet *et al*., 1989; Javaux, 1992; Garcia, 1993; Garcia *et al.,* 1996; Garcia and Dromart, 1997; Gaumet *et al.,* 1996; Gaumet, 1997; Collin, 2000] are probably of type 2 *sensu* Vail *et al.* [1991] that is, not related to generalised emersions. The series would not contain true lowstand prograding wedges, but only shelf margin wedges. The absence of such lowstands, and the gentleness of the platform slopes, undoubtedly explain the rarity (or even the absence) of re-sedimented neritic carbonates in the adjacent basins. On the edge of the Burgundian platform, the hemipelagic marl domains are therefore often without bioclastic or oolitic datum horizons, which could be correlated with the carbonate sequences of the neritic domains.

CALLOVIAN – OXFORDIAN CLAYSTONES

Lithology, depositional environments and mineralogy of argillites

Lithology

The claystones (middle Callovian to middle Oxfordian p.p.) form a unit of mainly argilo-silty sediments, hosting scarce carbonate beds, these being more frequent towards the summit. The total thickness of these argillaceous deposits varies from 100 to 160 m, in the Andra and oil exploration boreholes drilled in the eastern part of the Paris basin (fig. 1 and 2). The Andra boreholes contain the succession of the various geological formations (fig. 3) identified in the outcrops of the eastern part of the Paris basin, namely, in ascending order, the "Woëvre clays", "Terrain à chailles" – containing siliceous and carbonate nodules – and "Marnes des Éparges" [Thierry *et al.,* 1980; Debrand-Passard *et al*., 1980; Lefrançois *et al.,* 1996; Andra, 2005].

In the HTM102 borehole (fig. 3), taken here as a reference, the first deposits at the base of the unit consist of 1.10 m of finely bioclastic argillaceous limestones, with more marly seams bearing ferruginous oolites. They are overlain, over more than 30 m, by argillites and homogeneous argilo-silty marls. The ferruginous oolites at the base form lenticular deposits, since they are not present in the other boreholes of the M/HM site. The first lithological change within the argillites corresponds, over a thickness of about 4 meters, of a number of 10 to 20 cm thick limestone beds, rich in ammonites, brachiopods and crinoids. The overlying deposits are again made of relatively homogeneous silty argillites rich in ammonites and pyrite burrows (*chondrites*) over more than 50 m. The upper part of the unit, from mark 385 m, is more variable from a lithological point of view. It reveals alternating calcareo-marly and silto-carbonated mudstone beds or nodules, starting with a massive calcareo-argillaceous bed. This is the lateral equivalent of the outcropping "Terrain à chailles" Formation. The frequency of the carbonate beds increases towards the top of the borehole, up to the first nodular, argilo-dolomitic limestone levels rich in sponge spicules, which form the transition with the carbonate reef facies of the middle Oxfordian and upper Oxfordian. Flints are occasionally found in the nodular beds. Bioclasts of bivalves, brachiopods, crinoids, spicules of sponges and Serpulidae are common.

Depositional environments

Observation of the facies and microfacies of the argillaceous formations [Pellenard, 2003] allowed the identification of four associations of facies, which correspond to proximal to distal environments (fig. 3).

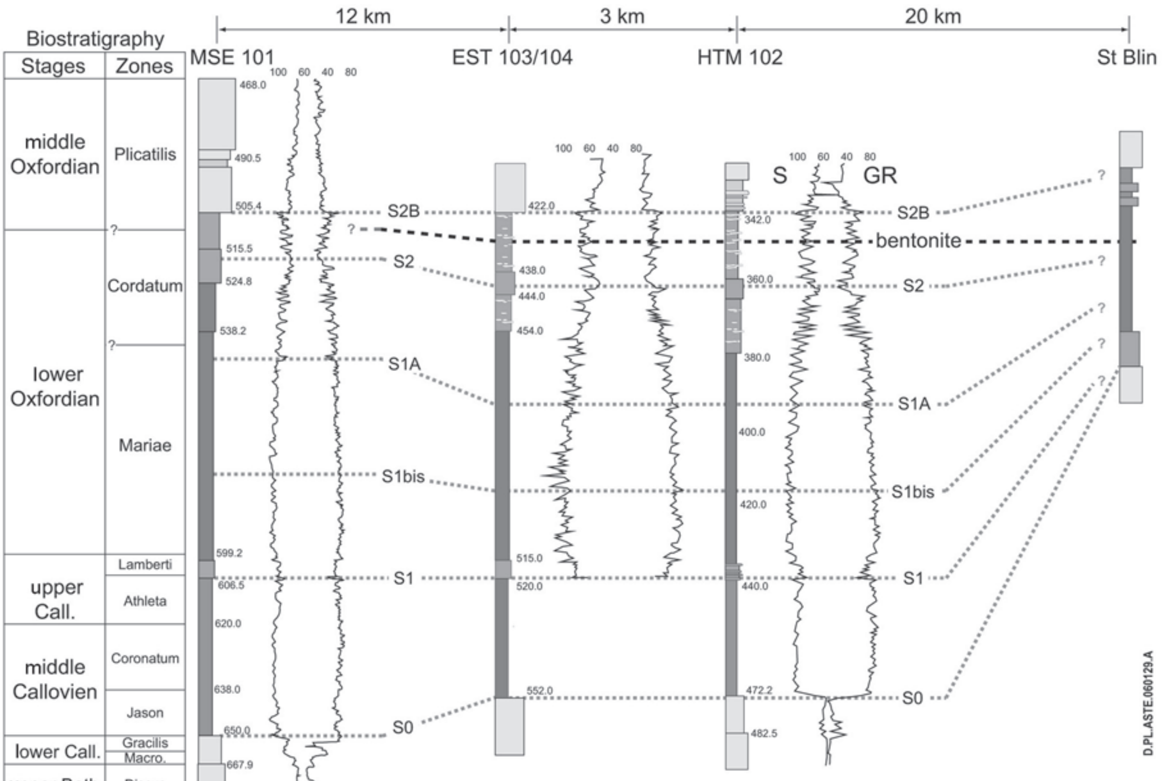

Fig. 2. – Stratigraphic position of the main key surfaces used for detailed correlations in the Callovian-Oxfordian clay formation at the scale of the Meuse/Haute-Marne area.
Fig. 2. – *Position stratigraphique des principaux repères utilisés pour effectuer les corrélations de détail dans la couche argileuse callovo-oxfordienne à l'échelle du secteur M/HM et de ses environs immédiats.*

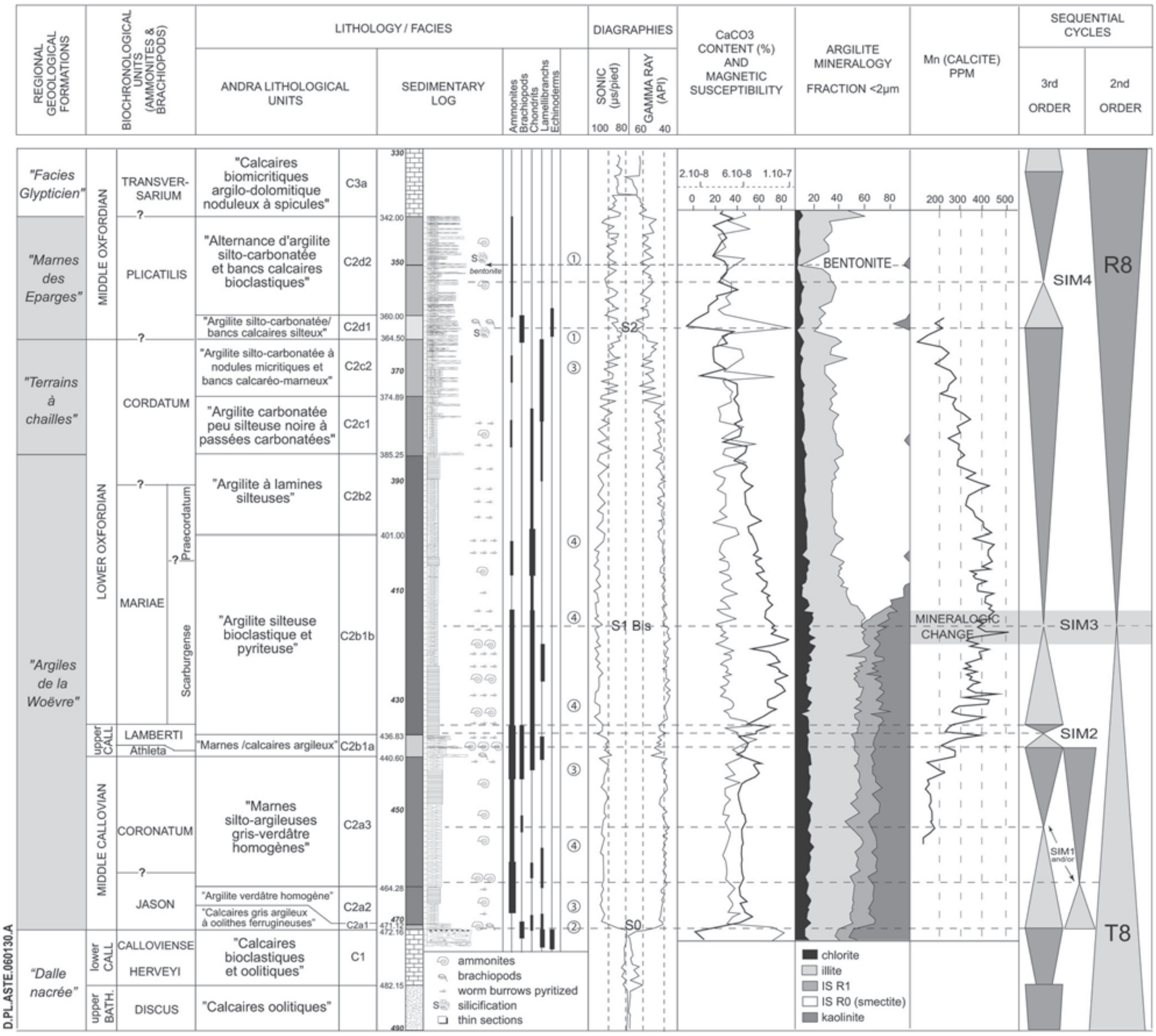

Fig. 3. – Sedimentology, mineralogy, geochemistry and sequence stratigraphic interpretation of the Callovian-Oxfordian clay formation in the Meuse/Haute-Marne area.
Fig. 3. – *Sédimentologie, minéralogie, géochimie et interprétation séquentielle de la couche argileuse callovo-oxfordienne dans le secteur M/HM.*

a) Wackestones bearing rhynchonellids, large bivalves and Miliolidae are evidence of a shallow-water middle platform environment. The presence of glauconite in some beds is evidence of a relatively open environment. The depositional environment could correspond to the upper middle offshore domain.

b) Argillaceous limestones containing ferruginous oolites and quartz grains at the base of the argillaceous formations have a wackestone texture. The benthic fauna includes sponges spicules, Pholadomyae, planctonic bivalves (*Bositra*) and foraminifers (lenticulines, trocholines). Their presence is clear evidence of a marine environment and good oxygenation. The abundance of mud suggests slight agitation in an upper distal to lower proximal offshore environment.

c) Marls and mudstones containing fine bioclasts of bivalves and grains of quartz, benthic foraminifers (*Epistominidae)*, spicules of Geodiidae sponges and ammonites are evidence of a deeper, open sea environment. Large numbers of filaments (prodissoconches of bivalves) and *Bositra*, together with the abundant micritic cement, suggest a lower middle offshore (external platform) environment with weak hydrodynamics.

d) The last, most common facies corresponds to silty argillites containing ammonites and prodissoconches. The abundance of fossils (C*hondrites)* and pyrite is evidence of a poorly oxygenated environment, attributed to a distal offshore (lower external platform) domain.

Mineralogy of argillites

The composition of the argillites (fig. 3) includes three main phases: clays, silts (quartz, feldspar mainly alaskite, micas of the muscovite and leverrierite type) and carbonates (calcite and dolomite). Feldspars, dolomite, micas and pyrite only form a small proportion of the rock (< 5%). The results [Andra, 1998; Pellenard, 2003] are obtained by direct measurement (petrographic and granulometric analyses, calcidolomimetry, semi-quantitative determination by diffraction of X rays, geochemical analyses) or indirect (calculation based on well logs).

Samples from the lower part of boreholes reveal a quite homogeneous composition in the ternary silt-carbonate-clay diagrams. The measurements made in the upper part of the series, that is the "Terrains à chailles" and "Marnes des Éparges" formations, are more heterogeneous and reveal the above-described lithological layering, with a trend towards a, first, more silty, then more carbonated pole [Andra, 1998]. The lithological variability at the scale of the Andra boreholes is revealed throughout the lower unit by a slightly higher clay content in the EST103/104 boreholes (close to the laboratory) and a higher silt content in MSE101 *vs* HTM102. The upper part is richer in carbonate and silt in MSE101.

The mineralogy of the clays obtained by X rays diffraction (DRX) according to the protocol developed by Brown and Brindley [1980], on closely-spaced samples (one sample/m to one sample/50 cm) throughout HTM102 borehole [Pellenard, 2003; Pellenard *et al.*, 1999], reveals assemblage of clay minerals, including kaolinites, chlorites, illites *s.l.,* disordered interstratified illite/smectite rich in smectite of type R = 0 (I-S R0, 45-75% smectites layers) comparable to smectites and ordered interstratified illite/smectite rich in illitic sheets of type R = 1 (I-S R1, 25-45% smectites layers). The semi-quantitative study carried out from the area of diffraction peaks reduces the uncertainty to 5% [Reynolds, 1989].

Two main mineralogical units may be distinguished in the argillaceous formation (fig. 3): a lower half where the kaolinite and illite are abundant and an upper half where the kaolinite is absent and the interstratified I-S R0 is abundant. The mineralogical transition occurs over a reduced thickness (8 m in HTM102 borehole) and is marked by a gradual modification in the type of I-S interstratified which goes from I-S type R1 at the base to I-S type R0 at the summit. At the same time, the concentration of illite is reduced and the kaolinite disappears. The same mineralogical characteristics may be seen in the two other boreholes.

Recognised dating-correlation elements

The bio-chronostratigraphic dating of the lithostratigraphic units, consisting in the recognition of biostratigraphic units, such as the faunistic zones, sub-zones and horizons, datum horizons, and the positioning of stages and sub-stages boundaries, is based on the systematic collection of macro and microfossils (ammonites, brachiopods, large foraminifers, spores and pollen) in the core samples of the Andra boreholes. New, fundamental data were therefore added to the existing regional biostratigraphy [Wolgemuth, 1883; Corroy, 1932; Maubeuge, 1955; Stchepinsky, 1958, 1969; Marchand and Thierry, 1977; Thierry *et al.*, 1980; Debrand-Passard *et al.*, 1980; Courville and Bonnot, 1998; Collin, 2000; Collin and Courville, 2000].

The vast majority of the new biochronological acquisitions [Andra, 2005] can be considered to be sound and reliable in terms of precision of the ammonites zones, very often of the sub-zone, occasionally even the horizon. These relative datings are the essential prerequisite for a precise straigraphic positioning of the remarkable surfaces and lithological key-horizons identified in the sedimentary succession. This calibration provides as many additional correlation elements and marking tools allowing, *in fine*, the integration of the sedimentary series in the bio-chronostratigraphic and sequential standard framework proposed for the Middle and Upper Jurassic in western Europe [Gradstein *et al.*, 1994; Thierry *et al.*, 1997; Cariou *et al.,* 1997; Hardenbol *et al.*, 1998; Jacquin and Graciansky, 1998; Gradstein and Ogg, 2004] and, more particularly for the Paris basin [Guillocheau *et al.,* 2000a, b; Robin *et al.*, 2000].

Biochronological data

Middle / upper Callovian boundary

The scarcity or even absence of ammonites and brachiopods in the boreholes, make it difficult to locate the limit between the middle and upper Callovian (Coronatum zone – Athleta zone) within the base of the claystone formation. The same is true in the scarce outcrops.

In HTM102 borehole, a fauna of ammonites in the Coronatum zone was collected in the interval 442.78 m to 471.88 m; a fauna of the Lamberti zone exists between 433.60 m and 440.65 m, but the Athleta zone (probable indices between 439.95 m and 440.65 m) was not characterised with certainty. The limit between the middle and upper Callovian may therefore be positioned between 440.65 and 442.78 m, in the first unit of silty claystones of the "Woëvre clays". The palynological associations [Jan du Chêne, 1995, 1996a-b; Andra, 1998] surveyed between 440 and 460 m, are related to a comprehensive interval covering the Coronatum, the Athleta and the Lamberti zones. They do not allow for fine correlations with the ammonite biozones.

In MSE101 borehole, this same limit may be placed near the summit of the first unit of finely bioclastic silty mudstones with filaments, above mark 619.69 m. The rare indices of the middle Callovian are below this mark and the upper Callovian (Lamberti zone) is only certain between the marks 606.06 and 606.26 m. The Athleta zone was not characterised.

Finally, the limit between the middle and upper Callovian was identified neither in EST103 and EST104 boreholes where the base of the argillaceous formation was not sampled, nor at the outcrop in a south-southeasterly direction, at Humbertville and Saint-Blin [Marchand and Thierry, 1977; Collin and Courville, 2000] where the corresponding beds do not outcrop or are perhaps actually missing.

Upper Callovian / lower Oxfordian boundary

In most boreholes, the Callovian – Oxfordian limit is very precisely located towards the lower third of the "Woëvre clays". It was not identified at Saint-Blin or at Humbertville, due to the absence of outcrops or possible gap of the corresponding beds.

It was placed at 433.60 m in HTM102, at the top of a more carbonated interval; the ammonites collected between 433.60 and 436.40 m provide a perfect illustration of the *paucicostatum* horizon, Lamberti sub-zone, Lamberti zone of the uppermost Callovian. Above mark 433.60, a fauna of the *scarburgense* horizon, Scarburgense sub-zone, Mariae zone of the basal Oxfordian is found. Thanks to the discovery of a specific fauna, it is also identified at 514.31 m in EST103, at the base of a marl seam with microfilaments. It is likely located between 513.90 m and 514.94 m in EST104, an interval without ammonites but preceded and followed by marl beds with microfilaments containing fauna of the *paucicostatum* horizon (terminal unit of the Callovian) and of the *thuouxensis* and *sarburgense* horizons (lowermost Oxfordian) respectively. Finally, in MSE101, a fauna of the Lamberti sub-zone between 606.06 and 606.26 m, and the Scarburgense sub-zone, *scarburgense* horizon from 599.23 m surround an interval without ammonites, where this limit probably lies, at the top of a bioclastic marl seam containing microfilaments.

The palynology datings [Jan du Chêne, 1995, 1996a-b; Andra, 1998] show considerable divergences and less precision than those given by ammonites; the Callovian – Oxfordian transition is placed towards 415 m in HTM102; that is, more than 18 m above the limit given by the ammonites, and between 560 and 600 m in MSE101, that is within a sedimentary interval 40 m thick, as opposed to less than 7 m using the ammonites.

Lower / Middle Oxfordian boundary

In the boreholes, neither the ammonites nor palynology did enable the Lower Oxfordian-Middle Oxfordian limit, placed in the reference scale, between the Cordatum zone and the Plicatilis zone, to be positioned very precisely.

The lower-middle Oxfordian limit could be placed between 368.30 m and 375.58 m in HTM102; this corresponds to the last ammonites of the lower Oxfordian, Mariae zone, Praecordatum sub-zone found at 381.35 m and the first ammonites of the middle Oxfordian found at 355.90 m. The study of the palynofacies at the transition between the lower and middle Oxfordian [Jan du Chêne, 1995, 1996a-b; Andra, 1998], in the interval 352-371 m, tends to confirm the positioning of the base of the middle Oxfordian. A set of concurring arguments leads us to place the lower-middle Oxfordian limit between 435.85 m and 446.80 m in EST103 and above 466.52 m in EST104. In EST103, the first ammonites of the middle Oxfordian appear between 433.74 m and 433.85 m above a set of more limy beds towards 441.50 m, generally characteristic of the beginning of the middle Oxfordian in outcrops and in the other boreholes. In MSE101, the limit could be close to 521 m: presence of brachiopods of the middle Oxfordian at 519.50 m; recognition of palynofacies characteristic of the transition between the lower and middle Oxfordian around 535 m; presence of limy beds from 521 m.

Age of the so-called "Callovian-Oxfordian" argillaceous series

According to the various boreholes studied (HTM102, MSE101, EST103 and EST104) and according to the fauna collected, depending of the cored intervals, all the biostratigraphic units of the standard scales of ammonites cannot be identified. This does not necessarily imply their absence, but affects the precision of datations and the possibility of correlations between the outcrops and the boreholes, which vary accordingly.

The argillaceous series begins, generally, with the Medea sub-zone, at the base of the Jason zone of the middle Callovian. Above the perforated surface of the "Dogger limestone", sedimentation could resume earlier very locally, with a condensed level which would be identified in HTM102, including the extreme summit of the lower Callovian, Calloviense zone, Enodatum sub-zone (= Patina).

It probably ends in the Plicatilis zone of the middle Oxfordian, including the stratigraphic equivalent of the "Terrains à chailles" and the "Marnes des Éparges", formations which were previously compared to the "Argovian facies" *auct*. However, the scarcity of ammonites in these last two formations which are gradually enriched in limestone beds, does not allow for greater precision, which obviously affects the positioning of the lower – middle Oxfordian limit discussed above.

The middle Callovian is extensively present in HTM102 and MSE101 where it is represented respectively, by 29.10 m and 29.93 m of sediments, the base of which (first decimetres) is very precisely dated of the Jason zone, Medea sub-zone. Above, in MSE101, the rather uncharacteristic ammonites found still indicate the middle Callovian without specifying the zone; in HTM102, the Jason zone and the base of the Coronatum zone cannot be distinguished over more than 20 m of deposits, whilst the summit of the Coronatum zone is clearly identified over the next 6.50 m. The middle Callovian was not identified in EST103 and EST104 boreholes.

In the four boreholes concerned, the upper Callovian is identified only over a very small sedimentary interval, dated from the Lamberti zone, Lamberti sub-zone; no data indicate the presence of the Henrici sub-zone (base of the Lamberti zone). It should be noted that in all cases, the beds located immediately above the middle Callovian (except in EST103 and EST104) contain no ammonites; these intervals of uncertainty are generally limited to a few decimetres of deposits (HTM102 and EST104) except in MSE101 where they reach a thickness of 13.50 m. This borehole is the one, which proved to be the least fossiliferous and, particularly between the marks 620 and 600 m, since the Lamberti zone was only identified on a thin sedimentary interval between 606.26 m and 606.12 m. On the other hand, when the Lamberti sub-zone of the Lamberti zone, is recognized, the precision of dating attains the horizon, with the standard succession: *praelamberti*, *lamberti* and *paucicostatum* horizons [Fortwengler, 1989; Fortwengler and Marchand, 1994; Fortwengler *et al*., 1997].

The lower Oxfordian and the Mariae zone are, respectively, the best recorded chronostratigraphic unit and biozone in the argillaceous series. The corresponding intervall of sediments is thick: 67.50 m in EST103; 51.75 m in HTM102; 46.80 m in EST104; 40 m in MSE101. The continuity of dating elements between the upper Callovian and the lower Oxfordian is remarkable in HTM102 and EST103 since the limit between the two stages (which is also the limit between the middle and upper Jurassic) is very precisely positioned. But, intervals of uncertainty exist in EST104 (1 m of sediment containing no ammonites) and in MSE101 (6.50 m); furthermore, the two sub-zones of the Scarburgense zone are not as clearly identified in these holes.

The Scarburgense sub-zone is the thickest and most fossiliferous biostratigraphic sub-unit. It often allows for breakdown up to the horizon precision. The *thuouxensis* horizon, the first unit of the Oxfordian, is clearly identified in EST103 and EST104, but not in HTM102 and MSE101. The *scarburgense* horizon – *woodhamense* horizon succession is found in detail in EST103, HTM102 and MSE101; nevertheless, intervals of uncertainty with variable amplitude exist for this precision threshold whilst at those of the zone and of the sub-zone, the sedimentary recording appears more continuous.

The base of the Praecordatum sub-zone, *praemartini* horizon, is clearly identified in MSE101. The same sub-zone exists in EST103 and HTM102, but its horizons cannot be distinguished. It is not identified in the upper 33.50 m cored of EST104, which are totally devoid of characteristic ammonites.

In all boreholes, ammonite faunas become increasingly rare, or even absent, above the last, clearly dated beds of the Scarburgense sub-zone or Praecordatum sub-zone. In particular, in MSE101 borehole, no precise dating elements were found between marks 559 m and 432 m. In EST103, indications of the middle Oxfordian were found between 433.85 m and 433.74 m, above an interval of uncertainty of 14 m. The upper 12 m cored interval of this borehole cannot be dated with precision but, following the arguments set out above, they probably belong to the middle Oxfordian. Regarding HTM102, some indications of the middle Oxfordian are found between 335.90 m and 347.68 m without any greater precision. Considering the position of the bentonite bed at 350 m (*see* § Preservation of a bentonite), and a possible lower-middle Oxfordian between 375.58 m and 368.30 m, the last beds used in this borehole to look for ammonites are probably in the Plicatilis zone.

Elements for well-log, event-stratigraphic, mineralogical and geochemical correlations

Well-log correlations and reference surfaces used

The high resolution well-log correlations carried out by DIASTRATA in boreholes, whether core or not, enabled us to identify and define six laterally continuous surfaces related to the carbonate/clay ratio (fig. 2). These surfaces have been traced throughout the sector studied [Andra, 2005].

Because they are constrained both by biostratigraphic data and by the position of the bentonite bed (fig. 2), these surfaces are considered as isochronous in first approximation. These surfaces are as follows:

– S0, (Top of the “Dalle nacre” or “Dogger limestone”), summit of the lower Callovian;

– S1, upper Callovian, Athleta zone (identified in HTM102 borehole);

– S1bis, lower Oxfordian, Mariae zone, Scarburgense sub-zone;

– S1a, lower Oxfordian, summit of the Mariae zone, Praecordatum sub-zone probable;

– S2, lower Oxfordian, Cordatum zone;

– S2b, middle Oxfordian, Plicatilis zone.

Sequence stratigraphy

The Callovian-Oxfordian sedimentary series is part of the 2nd order transgressive-regressive cycle T8/R8, starting at the middle/upper Bathonian boundary and ending at the base of the upper Oxfordian [Hardenbol *et al.*, 1998; Jacquin *et al.*, 1998] or covering the lower Bathonian – middle Oxfordian interval [Guillocheau *et al.*, 2000a, b]. Among the reference surfaces defined above, surface S1bis, which corresponds to the maximum clay content of the formation, coincides with the maximum flooding surface of this 2nd cycle *sensu* Jacquin *et al.*, [1998]. It also coincides with the main mineralogical change evidenced in the clays [Pellenard *et al.*, 1999, 2003; Pellenard, 2003], and as well to the higher values of Mn measured in the carbonate phase [Brégoin, 2003]. In addition, the analysis of ammonite fauna suggests a maximum paleodepth of the environment at this time.

At the 3rd order level, several depositional sequences have been defined from logs [Andra, 2005] or proposed on the basis of high resolution geochemical and mineralogical facies data [Pellenard *et al.,* 1999; 2003].

Within the Callovian-Oxfordian, well-logs enabled us to define 2.5 transgressive/regressive cycles whilst the data produced by the study of the cores have led to the recognition of 4, or even 5 cycles, given *i)* uncertainty about an additional cycle in the middle of the Callovian (fig. 3) *ii)* higher resolution and continuity of observations, allowing for the identification of an additional cycle in the upper Callovian, that is in the more condensed part of the argillaceous formation.

Furthermore, considering the whole depositional profile, from the inner platform (“seuil de Bourgogne” to the south-west) to the outer platform (Andra borehole sector), other, additional 3rd order cycles have been identified [Collin, 2000; Collin *et al.*, 2005; Courville and Collin, 2002]. These were not identified in the Callovian-Oxfordian argillaceous series because of the persistence of a relatively homogeneous outer platform facies, for the period concerned.

Preservation of a bentonite bed (instantaneous volcanic event)

A bed characterised by a monomineral clay (95% of dioctaedric smectites of the potassium rich, aluminium-iron bearing beidellite type) has been found in HTM102 borehole [Pellenard *et al.,* 1999] then in EST103 and EST104 boreholes in the expected stratigraphic position, constrained by well-logs correlations and biostratigraphic data. The comparison of petrographic (smear slides, thin sections, SEM), mineralogical (DRX, ATD) and geochemical analyses (majors, traces and rare earth elements) indicates very clearly that this is a level of volcanic origin formed by distal, aerial fallout of volcanic ashes, which was altered in clays during early diagenesis in a marine environment [Pellenard *et al.,* 2003]. Found in the section at Saint-Blin, 20 km to the south of the Andra boreholes and, on an even greater scale, in more than a dozen locations in the remote French sub-alpine basin, this bentonite is a correlating means of exceptional value. The validity of the correlations established for this level have been carried out using the comparison of the geochemical spectra and discriminatory analyses of traces and rare earths, which are less mobile when subject to alteration [Pellenard *et al.,* 2003].

The stratigraphic position of this datum horizon is not precisely defined in the Andra boreholes, given the scarcity of the characteristic ammonite fauna in the upper part of the argillaceous formation. In the St-Blin section where ammonites are more abundant and more characteristic, the bentonite lies approximately 0.80 m under a layer dated of the middle Oxfordian, Plicatilis zone and 1.80 m above another layer dated of the lower Oxfordian, Cordatum zone. In the sub-alpine basin where it is correlated geochemically, the precise biostratigraphic biostratigraphy of the "Terres Noires" [Fortwengler, 1989, Marchand *et al.,* 1990] gives an age from the base of the Plicatilis zone, Vertebral sub-zone [Pellenard *et al.,* 2003].

This bentonite bed is evidence of a paroxysmal volcanic event due to intra-plate alkaline volcanism, the most probable source of which is the volcanic complex of Zuidwal (Holland), which is situated less than 500 km to the north of the M/HM boreholes [Pellenard *et al.,* 2003]. It provides an extremely accurate and reliable means of correlation at the western European scale and which, in practice, may be used to characterise the base of the middle Oxfordian and more precisely the Vertebrale sub-zone.

Mineralogical change of the clays

The major change in clay assemblages (fig. 3), as discussed above in order to stratigraphically locate the position of the maximum flooding surface of the Bathonian – Oxfordian T/R cycle, occurs at the base of the lower Oxfordian, Mariae zone, Scarburgense sub-zone, *woodhamense* horizon, as it is dated in the St-Blin section [Collin and Courville, 2000; Pellenard, 2003]. It occurs throughout all Andra boreholes and appears isochronous according to well-log correlations and in the current state of the biostratigraphic data obtained from these boreholes. The mineralogy of the clays evolves in the same way in the boreholes and the St-Blin section: a gradual reduction in the illite proportions, reduction then disappearance of the I-S R1 and kaolinite in favour of I-S R0 (or smectites) towards the top. This change takes place within 8 m of deposits in HTM102 borehole and less than 5 m at Saint-Blin, within a sub-zone of ammonites. It provides an additional, regional chronostratigraphic marker.

A similar mineralogical change is known in Normandy, the Berry and the Boulonnais and in the northwestern part of the London-Paris basin, but is recorded as slightly diachronous. If it is indeed dated to the lower Oxfordian in England (Dorset and Berkshire), Berry and the south of the Armorique rim (Maine) as in the eastern part of the Paris basin. It seems to be younger, that is occurring by the transition between the lower and the middle Oxfordian, on the remaining part of the Armorique rim (Perche, Pays d'Auge) and in Boulonnais [Dugué, 1991].

This rapid, general change in the nature of clays cannot be explained through burial diagenesis, as shown by the various diagenetic studies carried out on the Callovian-Oxfordian sediments of the boreholes [Andra, 1998, 2005; Landais and Elie, 1999; Rousset and Clauer, 2003]. It is rather the result of a change in the sources of sedimentary contributions [Pellenard *et al.,* 1999]. The cause of this change is to be found in the paleogeographic and regional geodynamic evolution. It could be related to an early communication between the future North Atlantic in the process of opening and the Paris basin [Dugué, 1991, 2003; Pellenard *et al.*, 1999; Pellenard, 2003], a paleogeographic change that would induce a change in fine terrigenous contributions (see below).

Regional thickness changes, stratigraphic hiatus and diachronisms

The markers listed above together with the Andra 2D and 3D seismic data enabled us to monitor thickness variations of the Callovian-Oxfordian clays in the M/HM sector in detail.

It must be underlined first that throughout all Andra boreholes and in the Saint-Blin section, within the precision of sub-zone of ammonites, no hiatus appears between the summit of the upper Callovian (Lamberti zone) and the base of the middle Oxfordian (Plicatilis zone) thus minimising the possibility of any variations of the sedimentary pile in the limited M/HM sector. Nevertheless, it is possible that sedimentary disconformities and/or variations of facies and condensations exist. Given the sedimentary context dominated by clay and the precision of the biochronological dating; they should nevertheless, be minor, at the scale of the horizon or the sub-zone of ammonites, and limited to short periods. In contrast, the deposits of the lower and middle Callovian and of the base of the upper Callovian (Athleta zone) are often thin, occasionally condensed and incomplete on the outcrops, notably towards Burgundy [Courville and Collin, 2002; Collin *et al.,* 2005].

Furthermore, the recent synthesis of the boreholes and the outcrop data available for the entire eastern part of the Paris basin [Collin *et al*., 2005; Carpentier, 2004; Courville and Collin, 2002] shows that the Callovian-Oxfordian claystones filled a subsiding area, oriented WNW-ESE; this area lies between Reims, Verdun and Bar-le-Duc. The M/HM sector lies slightly south of the maximum thickness of the Callovian-Oxfordian argillaceous series. The correlation of all the data also reveals the relationship between the more carbonated condensed layers or those containing ferruginous oolites and the surfaces identified within the argillaceous series. These reference surfaces and condensed layers mix up on the Burgundy swell to the south (fig. 4).

Source of terrigeneous contributions

The mineralogical assemblages described above are probably the result of the alteration and erosion of rocks from the closest Hercynian massifs, known to have been emerged during the Callovian and Oxfordian period. Those are the London-Brabant Massif, Massif Armoricain, Rhenish Massif or Bohemian Massif. The Massif Central, which at this time, was probably immersed or very locally and temporarily emerged appears to have been a transit zone and not as a real source of terrigenous contributions.

Given the warm Jurassic climate, a considerable hydrolysis could have produced soils containing kaolinite or smectites and, at the same time could have released primary minerals, such as illite or chlorite from the acidic, crystalline bedrocks. The diversity of the clay assemblies studied across a large part of the Armorique rim, from the Bathonian to the upper Oxfordian [Dugué, 1991] is evidence of the complexity of contributions close to a continent. In the eastern part of the Paris basin, a much more distal sector, a mixing of fine terrigenous contributions from the various emerged domains may have occurred. The Ardennes province, which is mineralogically very distinctive (sedimentation dominated by smectites as early as the middle Callovian) and perhaps more prone to subsidence [Lefrançois *et al.,* 1996], acted as a trap for terrigenous

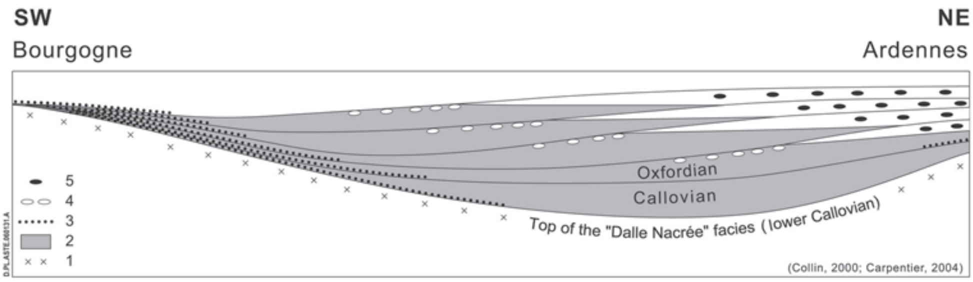

Fig. 4. – *Thickness changes in the Callovian-Oxfordian clay formation from the Ardennes to the Burgundy swell, from Carpentier's [2004] well log correlations.*
Fig. 4. – *Evolution schématique des épaisseurs de la couche argileuse des Ardennes au seuil Bourguignon, d'après les corrélations diagraphiques de Carpentier [2004].*

contributions from the north, at least during the Callovian [Pellenard, 2003].

The mineralogical change occurring during the early Oxfordian is the result of a significant change to the contribution sources, because identified in several domains of the London-Paris basin and perhaps at a larger scale in western Europe. Accordingly, two main sources of fine clastic contributions should be considered, in the middle Callovian to the middle Oxfordian intervall [Pellenard *et al.*, 1999; Pellenard, 2003]: 1); relatively proximal contributions of kaolinite, illite and chlorite, from the nearby emerged massifs, subject to alteration – erosion during older periods, that is, at least, during the Bathonian-Callovian period; 2) a distal contribution that favoured sedimentation dominated by smectitic minerals (interstratified I-S R0), from the beginning of the lower Oxfordian. This latter contribution probably resulted from significant paleogeographic modifications and, in particular, connections between basins, enhanced by higher sea levels during the maximum flooding of the second order cycle identified at the western European scale by Jacquin *et al.* [1998].

The origins of these clay species are still to be discussed. They will only be known with certainty with an increase of mineralogical data from the different sectors of the basin, provided that the biochronological resolution is sufficiently accurate elsewhere. The data currently available suggest the arrival of smectites from a domain in the western Atlantic (western approaches of the Channel and the Arctic-North Atlantic rift), through a peri-armorican trough [Dugué, 1991, 2003; Pellenard *et al.*, 1999; Pellenard, 2003]. This distal contribution appears to last until the middle Oxfordian for the eastern part of the Paris basin, at least. A late Callovian climate-cooling [Dromart *et al.*, 2003] could have also played a determining role in governing the conditions of humidity which control the pedogenesis and the formation of kaolinites. A strong change known in clay assemblages in the western European and Atlantic domains, *i.e.* the disappearance of kaolinite in favour of smectites, could reflect significant climate changes. The recording of the terrigenous signal in the Paris basin could therefore be due to a combination of paleogeographic, paleoceanographic and climatic changes at this time [Pellenard, 2003].

THE MIDDLE OXFORDIAN-UPPER OXFORDIAN CARBONATE PLATFORM

Stratigraphy

All biostratigraphic data available, together with the terminology of the lithostratigraphic units mentioned below are shown on the log of EST204 borehole drilled on the Bure laboratory site (fig. 5).

In the "Côtes de Meuse", shallow-water carbonate facies, which are at first uniformly coral bearing, are deposited on the Callovian-Oxfordian clays, after a transitional alternating facies of marl and limestone, often containing flint ("Terrain à chailles"), which is followed by the "Marnes des Éparges" Formation [see history of these formations *in* Carpentier, 2004]. The latter is thin and faciologically similar to the "Terrain à chailles" in the "côtes de Meuse" but becomes more marly and thickens towards the west (in particular to the south of Reims and to the west of Chalons-en-Champagne) [Carpentier, 2004]. At outcrops ("Côtes de Meuse"), the transition from the "Terrain à chailles" to the "Marnes des Éparges" occurs at the extreme base of the middle Oxfordian, Plicatilis zone [Poirot, 1987, *in* Carpentier, 2004]. The transition to the first coral facies probably occurred in the Plicatilis zone but without direct paleontological evidence [Enay and Boullier, 1981].

The first carbonate platform stratigraphically covers the entire middle Oxfordian. Its top is dated by ammonites from the base of the Bifurcatus zone (base of the upper Oxfordian) found in the base of the overlying marls [Enay and Boullier, 1981] (fig. 5). Within the carbonate formation, the ammonites once collected in the facies of "Creuë limestones" (lateral, inter-reefal equivalent of coral-bearing level P2 [Ferry, 2002] or "Euville Coral limestones" [Carpentier, 2004]) belong to the Transversarium zone, Parandieri sub-zone, of the middle Oxfordian [Enay and Boullier, 1981]. At the summit, the recent discovery [Carpentier, 2004] of an ammonite (*Subdiscosphinctes (Aureimontanites) sp.,* déterm. R. Enay) in the lateral oolitic facies equivalent of the "Maxey chalky limestones" indicates the Transversarium zone, Schilli sub-zone.

The correlation of the available borehole data [Carpentier, 2004] at a regional scale, shows that this first carbonate platform is overlain everywhere by an

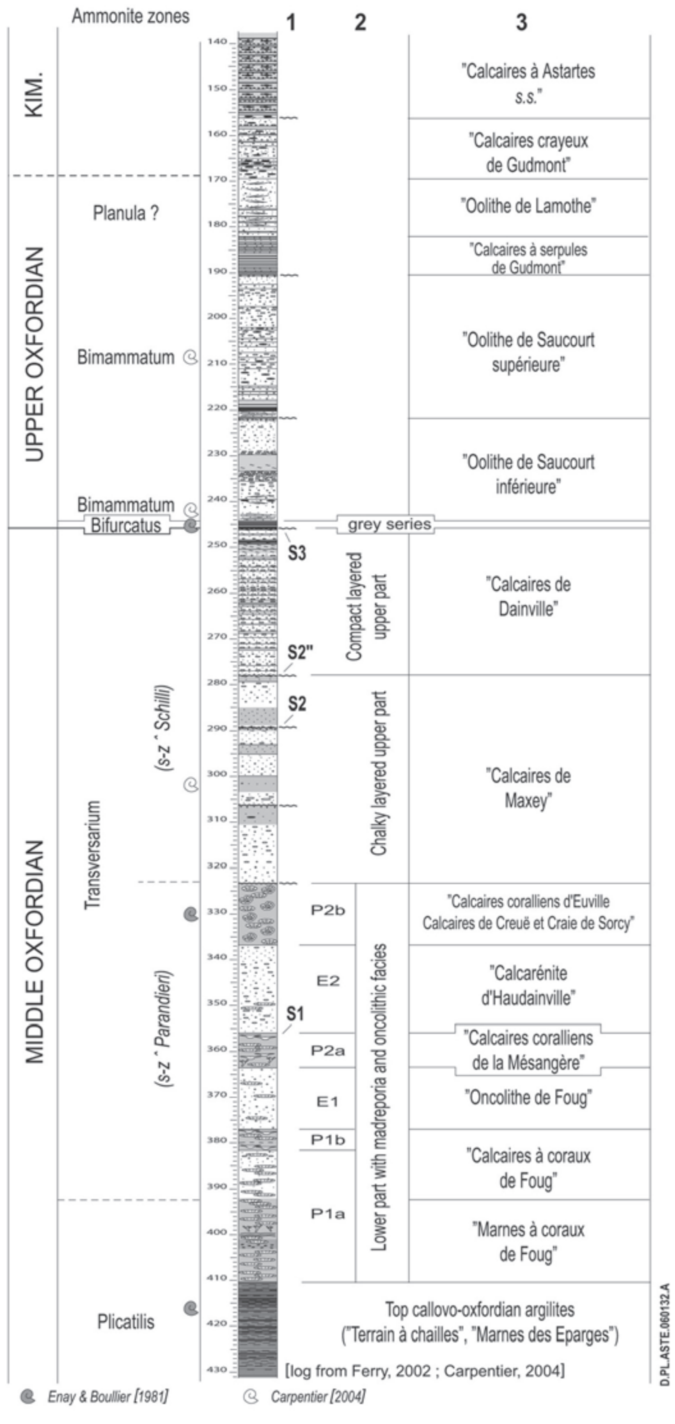

Fig. 5. – Detailed stratigraphy of middle to upper Oxfordian platform carbonates on the Andra site (well EST204).
1, local equivalent of the unconformities evidenced by Vincent [2001] in the HTM102 well; 2, lithostratigraphic units used by Ferry [2002]; 3, lithostratigraphic formations used and/or redefined by Carpentier [2004].
Fig. 5. – Stratigraphie détaillée des carbonates de plate-forme de l'Oxfordien moyen – supérieur sur le site du laboratoire de Bure (forage EST204).
1, équivalence locale des discontinuités identifiées par Vincent [2001] dans le forage HTM102; 2, *unités lithostratigraphiques distinguées par Ferry [2002]*; 3, *formations lithostratigraphiques distinguées à l'échelle régionale par Carpentier [2004].*

argillaceous unit (the "Grey series", fig. 6), dated of base of the upper Oxfordian at outcrop. We consider that the top of the first carbonate unit is about isochronous, due to a lack of more precise data.

In EST204 borehole (fig. 5), taken as reference in M/HM sector, the summit of the lateral equivalent of the "Marnes des Éparges", according to Carpentier [2004], and the transition to the first coral facies occurs towards mark 410 m, which could therefore, by correlation with the outcrops, define the base of the middle Oxfordian (Plicatilis zone). Its summit is located towards mark 245 m, which gives a local thickness of approximately 165 m for this first carbonate unit. The informal lithostratigraphic subdivisions adopted by S. Ferry [Ferry, 2002] have been included in a new lithostratigraphic scheme by Carpentier [2004] (fig. 6).

The second carbonate unit is 90 m thick in EST204 borehole, excluding the "Astartes limestones". It covers the major part of the upper Oxfordian and probably extends into the extreme base of the lower Kimmeridgian, in particular in Burgundy where the Astartes limestones, which overlie them are dated with better accuracy [Loreau and Thierry, 1975; Debrand-Passard *et al.*, 1980; Bernard, 1987]. In detail, this carbonate unit is complex (fig. 6) since it is made up of an alternation of limestones (often oolitic) and marls or finer-grained limestone facies. The facies vary from one region to another and, in particular in the lower part ("Grey series") where nested erosion surfaces have been evidenced in the Pagny-sur-Meuse quarry [Ferry, 2002; Carpentier, 2004, Fig. 71].

This second carbonate unit is poorly dated. The basal marls correspond to the extreme base of the upper Oxfordian. The "Pagny coral limestones" have recently provided two ammonites [Carpentier, 2004, déterm. R. Enay]: *Dichotomoceras bifurcatoïdes* in the lower part indicating the Bifurcatus zone, and *Perisphinctes hallatus* in the upper part, which indicates the Bimammatum zone of the upper Oxfordian. The "upper Saucourt oolite" still belongs to the Bimammatum zone, following the recent discovery of an ammonite at Pagny-sur-Meuse, *Lithacosphinctes decipiens-dewari* [Carpentier 2004, déterm. R. Enay]. The "Lamothe oolite" is placed in the Planula zone but without any direct paleontological data. The "Chalky limestones of Gudmont", defined by Carpentier [2004] as a lateral equivalent of the lower part "of the Astartes limestones" *lato sensu*, would be stratigraphically at the transition between the Oxfordian and the Kimmeridgian, according to brachiopods (*Terebratula subsella* and *T. suprajurensis*) discovered recently [Carpentier, 2004, déterm. A. Boullier].

Regional organisation

Middle Oxfordian carbonate platform

The boreholes in the M/HM sector, combined with new facies sedimentology studies in the field [Vincent, 2001; Ferry, 2002; Carpentier, 2004], considerably improve Humbert's lithostratigraphic scheme [1971].

The EST204 borehole (fig. 5) is used as a reference in the M/HM sector. The major discontinuities identified by Vincent [2001] and Vincent *et al.* [2004] in HTM102 borehole were identified in EST204 using porous horizons (see below), the lateral continuity of which is good at the limited scale of M/HM sector. The second porous horizon appears in this borehole in a facies which Vincent and others consider as "lagoonal", but which is probably a muddy interbiohermal facies of P2b (see below), as it has been identified both in outcrops and boreholes (EST204 and EST205) close to the Bure laboratory site itself.

The carbonate unit of the middle Oxfordian can be subdivided into two parts of roughly equal thickness in EST204 borehole (fig. 5). The lower part consists of alternating madrepore facies on the one hand and calcarenitic, oolitic and oncolitic facies, on the other. It thins out towards the "Côtes de Meuse" (fig. 6) where the different beds are still identifiable but tend to mix or nest [Ferry, 2002], with the exception of the last madrepore unit (P2b) the thickness of which is more constant and provides an important marker for lithological correlations between outcrops and boreholes. In the "Côtes de Meuse", emersions are common on the top of the coral subunits. The interbedded calcarenitic facies may not have the same facies as in EST204 borehole. This is particularly the case of level E1 (fig. 6), which takes a facies of coarse-grained crinoidal limestone (Entroquite) close at outcrops (level E, fig. 6). The Entroquite is transgressive (swash bar facies) on madrepore level P1, which is marked at the summit by emersion indices and truncated by a coastal abrasion platform (Euville quarries). In comparison with EST204 borehole, it is probable that level E1 represents a lowstand facies and that the Entroquite E only represents a younger, transgressive, part in the "Côtes de Meuse". In this interpretation, all the madrepore facies would represent shallow coral platform facies and the oncolitic facies would be deposited at a lesser depth. The sea level drops would induce emersions of the highest area of the coral platform ("Côtes de Meuse"), which would not occur in the Andra borehole sector.

In general, during this interval, the less subsident area of the "Côtes de Meuse" can be considered as a relative high and the most subsident area of the M/HM sector as relative low, or at least less subject to emersions, during this interval.

The correlation with the Joinville101 borehole (fig. 6) shows, by deduction that this lower carbonate unit should pass laterally into marl-limestone basinal facies west of the Marne valley. Indeed, the "Grey series" continues laterally from the "Côtes de Meuse" and is clearly visible in the Joinville borehole; it enables us to match the "Saucourt oolite" with the fine-grained limestones with thin oolitic intercalations found in the borehole and interpreted as a slope facies with storm layers. Similarly, the "Doulaincourt oolite" is considered as a lateral equivalent to a similar facies of fine-grained limestones interpreted as a slope facies, in accordance with the regional paleogeographic polarity [Guillocheau *et al.*, 2000a, b]. Similarly, in the Joinville borehole, the increase in thickness of the marl-limestone facies above the Argiles de la Woëvre is due to the lateral transition between the madrepore units and of the alternating beds of marls and limestones (fig. 6).

At outcrops, the "Doulaincourt oolite" presents a mixed, oncolitic and oolitic facies with spare corals, which is also clearly identified in EST204 borehole where it interfingers with the "Maxey chalky limestones" [Carpentier, 2004]. This observation enables us to stratigraphically match the whole "Doulaincourt oolite" with the white stratified limestones, which overlay the coral facies of the "côtes de Meuse". It is therefore highly unlikely to consider the "Doulaincourt

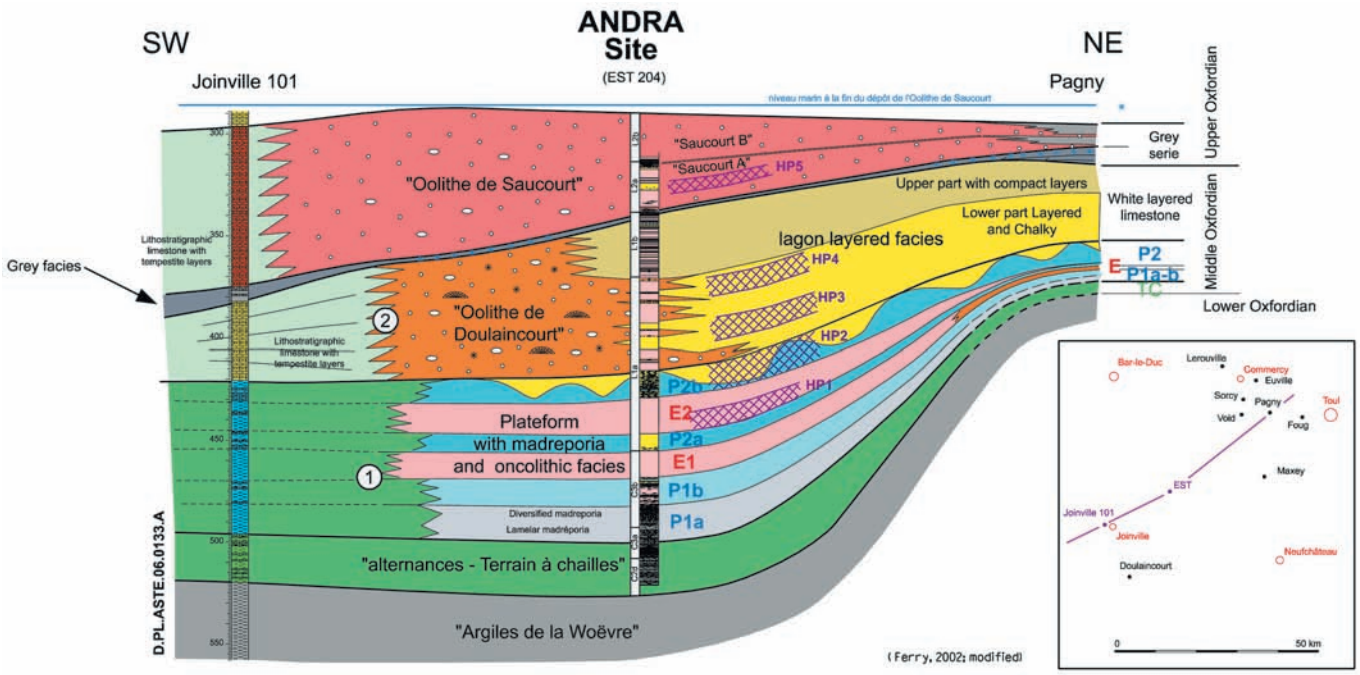

Fig. 6. – Regional stratigraphic organization of the middle to lowermost Upper Oxfordian deposits.
P1 to P2, main coral levels; E, crinoidal limestone of the « Cotes de Meuse »; E1 and E2, lateral equivalents, with oncolithic facies, of the crinoidal limestone E; HP1 to HP5, stratigraphic position of porous horizons evidenced in the Andra wells in the Meuse/Haute Marne area.
Fig. 6. – *Organisation stratigraphique régionale des calcaires de l'Oxfordien moyen et de la base de l'Oxfordien supérieur.*
P1 *à* P2, *principaux niveaux à madréporaires*; E, *entroquite des Côtes de Meuse*; E1 *et* E2, *équivalents latéraux, à faciès oncolitique, de l'entroquite*; HP1 *à* HP5, *position stratigraphique des horizons poreux reconnus en forages sur le secteur M/HM.*

oolite" as a barrier facies that would span the whole middle Oxfordian as earlier considered.

In this interpretation, it is clear that the carbonate platform of the middle Oxfordian consists of two units, the regional organisation and facies of which are different. The lower association with coral and oncolitic facies, with laterally continuous units, represents a very gentle ramp, from the "côtes de Meuse" (low thicknesses, frequent emersions, nesting of units) towards the South and West, where subsidence is also stronger (series twice as thick).

The upper facies association corresponds to another type of platform, with a mainly calcarenitic barrier and an internal, more muddy facies, of lagoon type, not previously interpreted as such (fig. 6). Emersion surfaces are common within this upper platform, starting with the one overlying the bioherms of unit P2b (fig. 5). Three emersion surfaces are identified in and at the summit of the "chalky" part ("Maxey limestones"). The upper "stratified, compact" part ("Dainville limestones") is made up of a very large number of emersive sequences, the thickness of which is inframetric to metric, starting with green clays overlain by muddy lagoonal facies.

This upper part is overally aggrading.

The validity of the correlation scheme of figure 6 [Ferry, 2002] is supported by the detailed regional well-log correlations carried out by Carpentier [2004].

Marine flooding at the beginning of the late Oxfordian

The laterally continuous marly "Grey series" (fig. 6), marks an overall change in sedimentation at the extreme base of the upper Oxfordian. This change may be found as far as the Swiss Jura and the Swabian Jura in platform domain [Gygi *et al*., 1998; Gygi, 2000]. We also found traces of it in the deep French sub-alpine domain [Gaillard *et al*., 1996]. The issue is assessing whether the change from limestones to marls can be interpreted as an indication of a generalised marine submergence or attributed to other causes, climatic for instance. The return of ammonites in the "Grey series" is such an indication, but the geometrical analysis of the formation in the upper levels of the Pagny quarry, reveals oolitic intercalations with tidal channel facies and gullied erosion surfaces in the grey marly limestone, before the deposit of grey coral limestones [Ferry, 2002; Carpentier, 2004]. Carpentier [2004] interprets these surfaces as the result of high frequency oscillations (glacio-eustatic?) of relative sea level at the time of submergence. This author applies the theory of double eustatism developed by Ferry [1991]. In any case, submergence is very limited based on depositional facies. It appears to be at its maximum for the coral facies of Pagny [Olivier *et al*., 2004]. If the carbonate platform of the middle Oxfordian could not have accommodated the small space created, a moderate flooding, it is because another reason must be found for the temporary disappearance of carbonates; in this case, the hypothesis of climate cooling acting on the production of carbonates could be thought of [Pittet, 1996; Dupraz, 1999; Dromart *et al*., 2003].

Upper Oxfordian carbonate platform

The main change, which accompanies the transition to the upper Oxfordian is a slight regional tilting movement [Carpentier, 2004]. The northern part of the platform, towards the Ardennes, deepens and receives terrigenous contributions from the emerged part of the Brabant. Such contributions are especially important a little further to the west, in the Reims region. The resistant zone, which will be basis for the return of carbonate facies in the late Oxfordian is also located close to the present day Marne valley but has moved slightly SW, towards the marl-limestone basin of the south of the Paris basin. It may be considered that the platform is globally aggrading, above the previous carbonate platform, but with less accommodation more during the rest of the sub-stage.

The upper Oxfordian platform is made up of three depositional cycles where carbonates are mainly oncolitic and oolitic, bearing sparse madrepore, with a facies similar to that of the "Doulaincourt oolite" (fig. 6). The oncolitic and oolitic facies constitute the major part of the series in the M/HM sector, which is located very close to the barrier area. They thin out to the north and north-east, towards the "Côtes de Meuse". At Pagny, only intercalations of distal storm facies can be found in the "grey series" which covers a time span longer than in the M/HM sector. The examination of facies relationships in the Pagny series shows that the two levels of Saucourt oolite rest sharply on the deeper marly limestones. They are each followed by marls with storm layers. It is therefore clear that the deposition of the oolitic facies corresponds to a drop in relative sea level. Each oolitic unit is then deposited with an aggradational pattern on the barrier and with a landward stepping pattern in the deeper, internal basin located to the north [Ferry, 2002; Carpentier, 2004, Fig. 87]. Thicknesses vary in accordance with this scheme: they are almost three times larger on the barrier than to the north (50 m for the "Saucourt oolite" in EST204 borehole, 15 m for the equivalent series at Pagny).

Paleogeographical maps

On the basis of an exhaustive study of the boreholes available for the whole western area of the Paris basin, a series of paleogeographical maps was made [Carpentier 2004]; the main evolutionary stages of the domain concerned are shown on figure 7.

Map A (fig. 7) represents the minimum areal extension of the basal argillaceous facies.

The madrepore facies were deposited on the Callovian-Oxfordian argillaceous extensively at the base of the Transversarium zone (map B). But this apparent homogeneity conceals a high level of complexity at a detailed scale. Areas 1 and 2 reveal more varied facies and shallower madrepore associations than elsewhere. During episode P2b (fig. 6), interbiohermal domains reveal a fine, stratified, ammonite bearing facies lying in two corridors running NE-SW and parallel to the direction of the Metz fault system. Sector 2 is located close to the Vittel fault.

Map C (fig. 7) represents the state of the aggrading platform during the second half of the middle Oxfordian.

This platform was anchored both on the Ardennes to the north and on the Burgundy swell to the south. In the "Côtes de Meuse", various sedimentological indicators (beach prisms oriented to the NE, north of St Mihiel-Dompcevrin, inversely oriented *spillover* lobes in the Pagny lagoonal limestones) reveal that the platform was facing a Germanic sea subject to severe swell and storms from the NE. In detail, the platform is broken down into two lagoon areas,

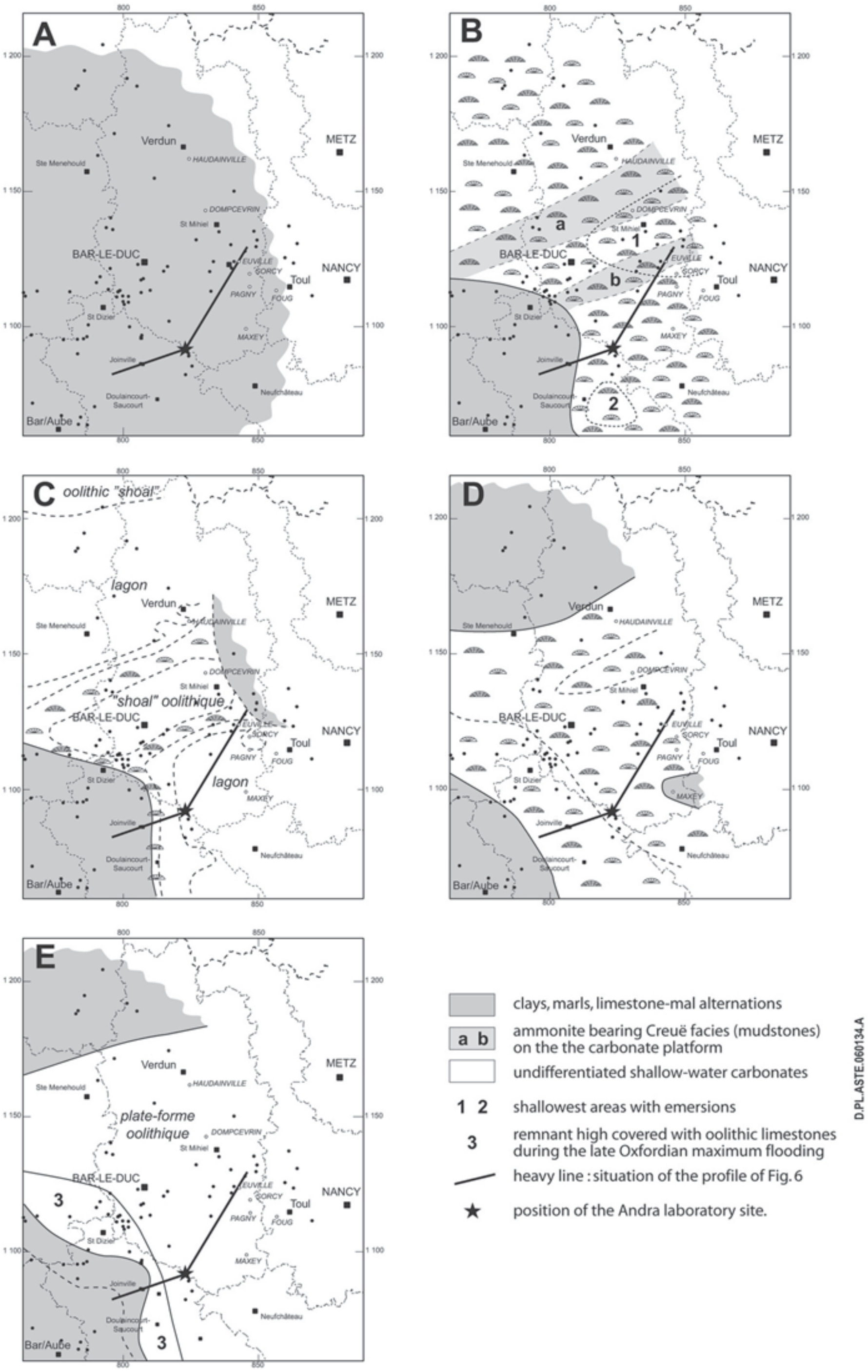

Fig. 7. – Facies maps covering the whole Oxfordian (regressive part of the Bathonian-Oxfordian major T/R cycle)
A, lower Oxfordian (lower part of the Woëvre marls formation); B, middle Oxfordian (lower part of platform carbonates, coral-bearing and oncolithic facies); C, middle Oxfordian (upper part of platform carbonates, chalky bedded facies, oolithic/oncolithic facies, locally coral-bearing); D, upper Oxfordian, maximum flooding (coral-bearing limestones of Pagny); E, upper Oxfordian, Saucourt Oolithe.
Caption: dark gey: clays, marls, limestone-mal alternations; light-grey: ammonite-bearing Creuë facies (mudstones) on the carbonate platform; white: undifferentiated shallow-water carbonates; 1 & 2: shallowest areas with emersions; 3: remnant high covered with oolithic limestones during the late Oxfordian maximum flooding; heavy line: situation of the profile of figure 6 ; star: position of the Andra laboratory site.
Fig. 7. – *Cartes paléogéographiques successives pour l'intervalle Oxfordien inférieur – Oxfordien supérieur (partie R du cycle bathonien-oxfordien).*
A, *Oxfordien inférieur (partie supérieure des « Argiles de la Woëvre)*; B, *Oxfordien moyen (partie inférieure de la plate-forme carbonatée, faciès oncolithiques et à madréporaires)*; C, *Oxfordien moyen (partie supérieure de la plate-forme, faciès lités crayeux, oolithiques et/ou oncolithiques, localement à coraux)*; D, *Oxfordien supérieur, maximum d'ennoyage (calcaires à coraux de Pagny)*; E, *Oxfordien supérieur, Oolithe de Saucourt*.

one to the north anchored on the Ardennes, the other to the south. Between the two, oolitic facies were deposited with intercalations of coral bioherms, i.e. a more open-marine facies. The latter area forms some kind of a corridor between the two main lagoons; as above, it runs parallel to the direction of the Metz fault system.

Towards the marl-limestone basinal facies, the south-west boundary of the platform is stable during the middle Oxfordian. It fits approximately with the Marne valley.

The general tilting movement, which marks the base of the late Oxfordian displaces the boundary of the carbonate platform slightly towards the south-west (map D, fig. 7). As a consequence, a deeper marl-limestone basin develops to the north. Coarse terrigenous influences (sandstones) occur further to the west (region of Reims). On the southern flexure (St-Dizier, Joinville, Doulaincourt), the coral facies of maximum submergence (passage between the Bifurcatus zone and the Bimammatum zone) are slightly more bioclastic and shallower. A similar facies is found along a north-east – south-west axis, north of St-Mihiel.

The oncolitic and oolitic platform of the upper Oxfordian is also anchored on the St-Dizier–Doulaincourt swell, which was probably uncovered during drops in relative sea level. At this time, lowstand calcarenites extended into the northern marl-limestone basin. During rises in sea level, the oolitic facies retreated north to south and aggraded on the ridge where it reaches its maximum thickness. This scheme is reproduced twice during the deposition of the "Saucourt oolite." The southern basin tends to fill by the end of the Oxfordian ("Lamothe oolite"). This local filling is a precursor to a global change, at the scale of the Paris basin; it marks the passage to the vast Kimmeridgian basin of "Virgula marls".

Synsedimentary influence of the present day system of faults

The clearest paleostructural feature is the matching of the isopic lines with the direction of the Metz fault system at some stratigraphic levels. This situation is also known in Bajocian platforms limestones [Thiry-Bastien, 2002]. Regarding the Vittel fault, we find no signs of real synsedimentary tectonic activity during the interval, concerning the distribution of thicknesses or facies, in particular in the argillaceous layer. We note a temporary coincidence between the south-west boundary of the Oxfordian carbonate platform and the Marne valley fault system in the St-Dizier-Joinville area. But we also see that the facies boundaries moves considerably during the interval. Finally, the isopachs maps made by Carpentier [2004] for the whole upper Callovian – upper Oxfordian interval reveal, independently of the zones of facies, significant movement of areas of maximum subsidence; these basins do not always match the system of faults identified.

To summarise, it is probable that certain faults may have induced flexures in the summit of the sedimentary cover or a subsidence differential, but this movement is slight given the small variations in thickness in relation to the distances concerned. Over time, these local differences are compensated for globally.

Porous levels [HP]

Both on the outcrop in the "Côtes de Meuse" and in boreholes drilled by Andra, the limestone facies of the middle Oxfordian and, to a lesser extent, those of the upper Oxfordian, are more or less chalky. Porosity, calculated on the basis of neutron logs [Curial, 2000], may reach values of more than 20% in some "porous levels", numbered HP1 to HP5 below to the Bure laboratory site (fig. 8). The stratigraphic position of these horizons is shown on the figure 8.

The first nanoscopic examinations [Vincent, 2001] reveal that a subeuhedral micrite replaces the structure of the carbonate sedimentary grains, and the primary micrite as well. Similar observations have been made in Urgonian

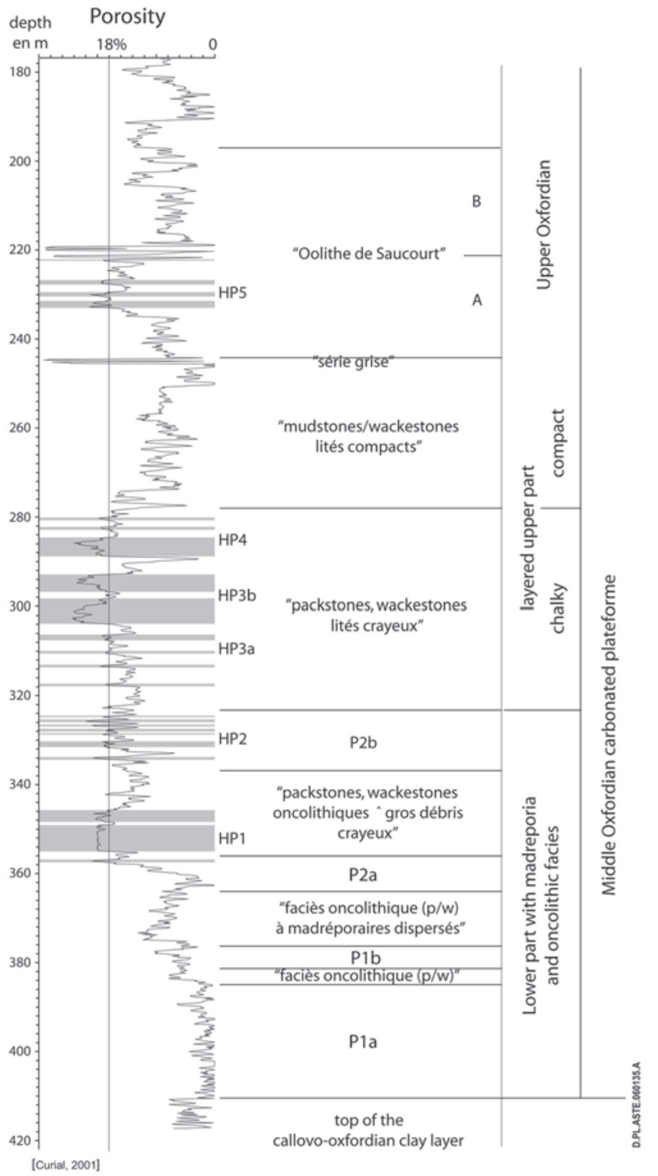

Fig. 8. – Vertical changes in the secondary porosity affecting Oxfordian platform carbonates in the ES 204 well.
DIAGEVAL® porosity calculated from well log values [Andra 2001]. Porous horizons HP as defined from porosity values above 18%. P1a to P2b, main coral-bearing units.
Fig. 8. – *Répartition de la porosité secondaire dans les calcaires oxfordiens de plate-forme du forage EST204.*
Porosité DIAGEVAL calculée d'après valeurs diagraphiques [Andra 2001]. Horizons poreux HP définis par des valeurs de la porosité neutron supérieures à 18%. P1a *à* P2b, *principaux niveaux à madréporaires.*

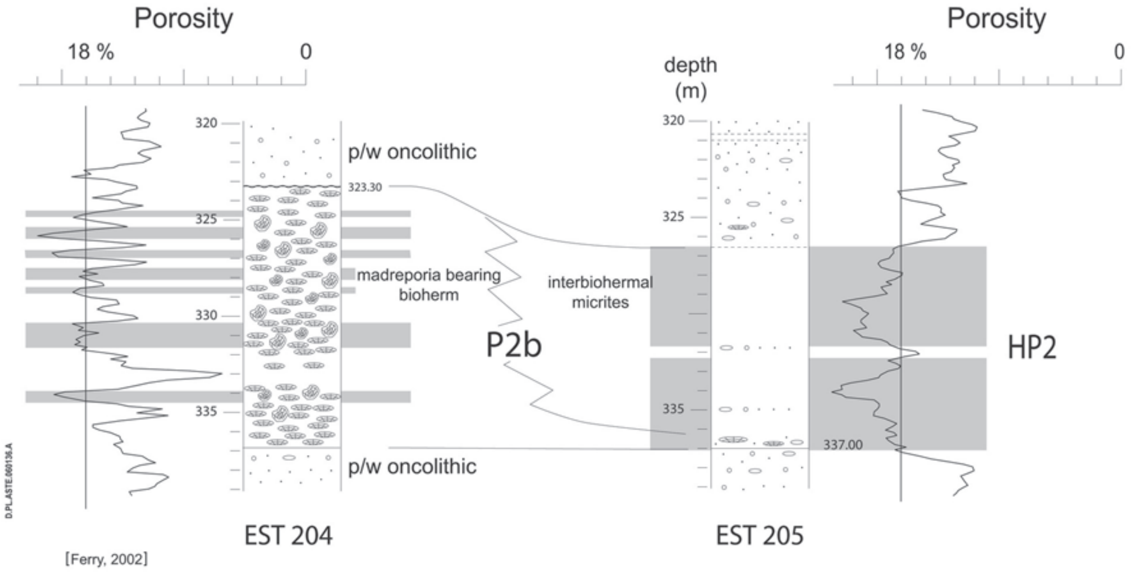

Fig. 9. – Porosity changes as a function of depositional facies between the closely spaced wells EST204 and EST205 on the Andra site of Bure. DIAGEVAL® porosity calculated from well log values [Andra, 2001]. Porous horizons HP as defined from neutron porosity values above 18%.
Fig. 9. – Répartition de la porosité en fonction du faciès dans l'horizon poreux HP2 entre les forages EST204 et EST205 sur le site du laboratoire de Bure. Porosité DIAGEVAL calculée d'après les valeurs diagraphiques [Andra, 2001]. Horizon poreux HP défini par des valeurs de la porosité neutron supérieures à 18%.

chalks (Barremian) of the lower Rhone valley [Hamdan, 1977]. This is clearly a secondary transformation since the primary structures of the carbonate grains have disappeared. This phenomenon affects many limestone formations of platform type [Moshier 1989a, b] which, accordingly, are likely to have been emerged or subject to the action of meteoric waters, or deep formations wich have never been emerged, such as Barremian oolitic turbiditic formations from paleoguyots in the central Pacific [Ferry and Schaaf, 1980]. In spite of its interest in the field of oil and gas exploration (gas bearing chalks), the process has not been subject to fundamental studies until now unlike the reverse process, cementation and hardening of nanofossil ooze (primary chalks). For chalks formed by diagenetic decay, various interpretations have been proposed. The explanations are very varied, from precocious recrystallisation in a marine environment or under the action of fresh water, to late diagenesis during burial [Ahr, 1989; Budd, 1989; Dravis, 1989; Kaldi, 1989; Moshier, 1989a, b; Perkins, 1989; Reid and McIntyre, 1998, 2000]. Clearly, the mechanisms are not yet fully understood.

By seismic signal inversion, it is possible to show [Barnola and Kuhfuss Monval, 2004] that the shape of these porous horizons is not regular in space inside the carbonate formation. Their overall arrangement is stratiform but their upper and lower boundaries are irregular, so that some may communicate locally.

Their possible connection, either with depositional facies or with major stratigraphic surfaces, such as emersion surfaces in the many genetic sequences making up the limestone formation, is still not clear. Several hypotheses have been proposed [Ferry, 2002]. In some cases (horizon HP2), porosity tends to affect the fine facies of the interbiohermal spaces of the coral level P2 (fig. 9) first. Since the madrepore are completely recrystallised, they tend to reduce global porosity in the bioherms. In this case, there is a clear link with the facies and the geometry of the deposit. In other cases, porous levels occur in rather homogeneous facies (oolitic grainstones or oncolitic wackestones/packstones).

The regional continuity of these HP is not known. The examination of the "sonic" logs available from old boreholes in the eastern part of the Paris basin shows that their stratigraphic distribution is variable and their lateral continuity probably poor (fig. 6) at the deca-kilometric scale. Their connectedness therefore remains uncertain.

In the M/HM sector, however, these porous horizons are more developped towards the east, in zones close to outcrops. They thin out and gradually disappear towards the centre of the basin [Vigneron *et al.*, 2005].

CONCLUSIONS

The new stratigraphic data obtained recently, thanks in particular to the work of Andra in the Meuse/Haute-Marne sector, enable us to make precise regional correlations, both in the Callovian-Oxfordian argillaceous layer and in the overlying limestones of the Oxfordian platforms.

On the generally isochronous top (lower Callovian summit; Gracilis zone, Sub-Calloviense zone or Enodatum sub-zone) of the limestone facies of the Dogger platform ("Dalle nacre"), capped by a sedimentation omission surface indicating a major discontinuity at the scale of the Paris basin, the deepest argillaceous sedimentation of the Callovian – Oxfordian occurred diachronically. This resumption of sedimentation is increasingly later (lower Callovian summit; Gracilis zone, Enodatum sub-zone; base of the middle Callovian, Jason zone, Medea sub-zone) from north to south, from the Ardennes to the Burgundy platform, which was gradually immersed. This diachronism represents the progradation towards the south of an argillaceous wedge, the thickness of which decreases in this direction. These differences in thickness do not affect the excellent lateral continuity of all stratigraphic markers.

The mineralogical study of the clays reveals a rapid change in the nature of the interstratified illite-smectite minerals, isochronous at the scale of the M/HM sector, and dated precisely (base of the lower Oxfordian, Mariae zone, Scarburgense sub-zone, *woodhamense* horizon). Associated with the disappearance of kaolinite, it coincides with the maximum flooding surface of the major Bathonian-Oxfordian transgressive/regressive cycle, where the clays represent the deepest facies.

The setting of the carbonate platform of the middle Oxfordian (base of the Transversarium zone) is slightly diachronic from north to south. This platform passes from a gently sloping ramp (and/or more subsident) from the "Côtes de Meuse" towards the south to an aggrading platform with the appearance of typical lagoonal facies near the end of the middle Oxfordian. A slight tilting movement of the entire platform towards the Ardennes accompanied a moderate overall deepening at the base of the upper Oxfordian (Bifurcatus zone), marked by the regional deposition of grey clays. It accelerated, as an after effect, the progradation of the carbonate platform towards the south and caused an heterogeneity of facies towards the Ardennes with intercalations of sandstones in the grey clays.

The isopach maps at different levels of the Callovian-Oxfordian argillaceous layer show slight displacements of maximum thicknesses. These variations are due to regional irregularities in subsidence. They are generally compensated throughout the Callovian-Oxfordian period concerned. The link with the system of faults identified is not always very clear. Major faults, such as the Vittel fault do not seem to play a major sedimentary role on the deposition of the argillaceous series. In the carbonates of Oxfordian platforms, some faults may have temporarily driven the distribution of facies or thicknesses, but such movements are extremely slight, with regard to the lateral variations observed.

Finally, it should be pointed out that the Oxfordian limestones underwent a diagenetic decay into chalk, the mechanisms, age and regional distribution of which have still to be studied.

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