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Integrated stratigraphy of the Jurassic and the Cretaceous: a tribute to Jacques Rey /
Stratigraphie intégrée du Jurassique et du Crétacé : un hommage à Jacques Rey

The Oxfordian–Kimmeridgian transition in the Boulonnais (France) and the onset of organic-rich marine deposits in NW Europe: a climatic control?

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Abstract. We characterised the organic matter content of marine deposits at the Oxfordian–Kimmeridgian transition in the Boulonnais (France). Organic rich deposits in platform environments are evidenced in the uppermost *Cymodoce* and lowermost *Mutabilis* Zone (early late Kimmeridgian), associated with enhanced planktonic palaeoproductivity and/or developing dysoxia/anoxia. Similar organic rich intervals in early late Kimmeridgian are also evidenced in platform deposits in Normandy and Charentes in France, and in basinal deposits from Yorkshire and Dorset in UK. This refined onset of the organic rich bands (ORB), as described in NW Europe during the late Jurassic, is coeval with seawater warming. We propose that this seawater warming was an important trigger of the onset of the late Jurassic ORB deposition system in NW Europe, which began at the *Cymodoce–Mutabili*s boundary during the early late Kimmeridgian and lasted until the middle part of the Tithonian, over a time span of 6.8 Myr.

Keywords. Jurassic, Organic geochemistry, Palynofacies, Palaeogeography, Palaeoclimate, Palaeoproductivity, Organic rich band.

1. Introduction

Organic matter enrichments in marine deposits may be driven by a number of factors, such as tectonics, palaeogeography, climate and sea-level changes [Demaison et al., 1983, Tissot, 1979, Tyson, 1995]. Those factors can favour palaeoproductivity changes and/or induce anoxia/dysoxia in sea water masses, therefore leading to enhanced organic matter influx to the seafloor [Tyson, 1995]. During the late Jurassic, the upper Kimmeridgian–Tithonian deposits of several NW European basins do show such remarkable organic matter-rich intervals. Because of their significant contribution to the genesis of the North Sea hydrocarbons, those deposits were intensely stud-

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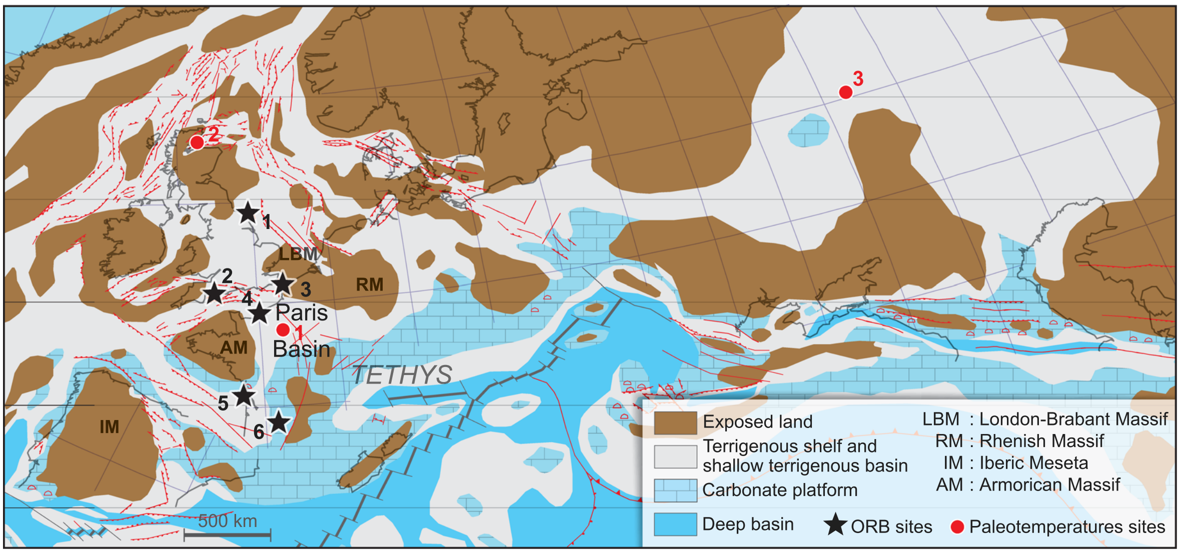

Figure 1. NW Europe paleogeographic map for the Early Kimmeridgian [Cecca et al., 1993]. Black stars: Organic-rich bands (ORB) sites cited in this work, 1: Yorkshire; 2: Dorset, 3: Boulonnais (this work), 4: Normandy, 5: Charentes, 6: Quercy. Red dots: selected sites with published sea-water paleotemperatures, 1: Paris Basin [Brigaud et al., 2008, Dera et al., 2011, Lathuilière et al., 2015]; 2: Scotland [Nunn and Price, 2010]; 3: Russian platform [Price and Rogov, 2009].

ied during the last decades, both in England [e.g. Cox and Gallois, 1981, Herbin et al., 1991, 1993, Huc et al., 1992, Morgans-Bell et al., 2001, Oschmann, 1988, 1990, Tyson, 1996, Tyson et al., 1979, Wignall, 1991] and northern France [e.g. Bialkowski et al., 2000, El Albani et al., 1993, Geyssant et al., 1993, Herbin and Geyssant, 1993, Herbin et al., 1995, Proust et al., 1995, Ramdani, 1996, Tribovillard et al., 2001, Waterhouse, 1999]. Well studied in the basinal facies of the so-called Kimmeridge Clay Formation in Yorshire and Dorset in UK, five ORB, for organic rich bands [Cox and Gallois, 1981] or organic rich belts [Herbin and Geyssant, 1993], have been described and correlated within these basins from the *Eudoxus* ammonite zone (late Kimmeridgian) until the *Hudlestoni–Pectinatus* zones (early Tithonian) [Cox and Gallois, 1981, Herbin and Geyssant, 1993, Herbin et al., 1993, 1995]. In the Boulonnais area in NW France, where more proximal, shoreface to outer platform facies were deposited during the upper Jurassic (Figure 1), the first two ORB as recorded in UK are not observed, and the three following ORB are only partly recorded [Herbin et al., 1995]. Both in UK and France, the largest organic matter enrichments correspond to the highest sea-levels recorded in this time period, in the latest Kimmeridgian to earliest Tithonian [Herbin et al., 1995, Wignall and Ruffell, 1990]. By contrast, the lower Kimmeridgian deposits received little attention because of the lack of oil-generating levels and the relative condensation of the sedimentary sequence and, as a consequence, the onset of this ORB deposition system is not well known.

In this paper, we aim to study the organic matter distribution at the Oxfordian–Kimmeridgian transition in the Boulonnais area in France, in order to detail the initiation of ORB deposition. We then compare the Boulonnais record with that of neighbouring regions in France (Normandy, Charentes, Quercy) and in the UK (Yorkshire and Dorset) and use known relative sea-level changes and a set of palaeoclimate data (namely seawater temperature reconstructions using stable isotopes) during the late Jurassic to discuss the possible triggers controlling ORB initiation and deposition at NW European scale.

2. Material and methods

In the Boulonnais area, late Jurassic deposits crop out on coastal cliffs north of the town of Boulogne-sur-

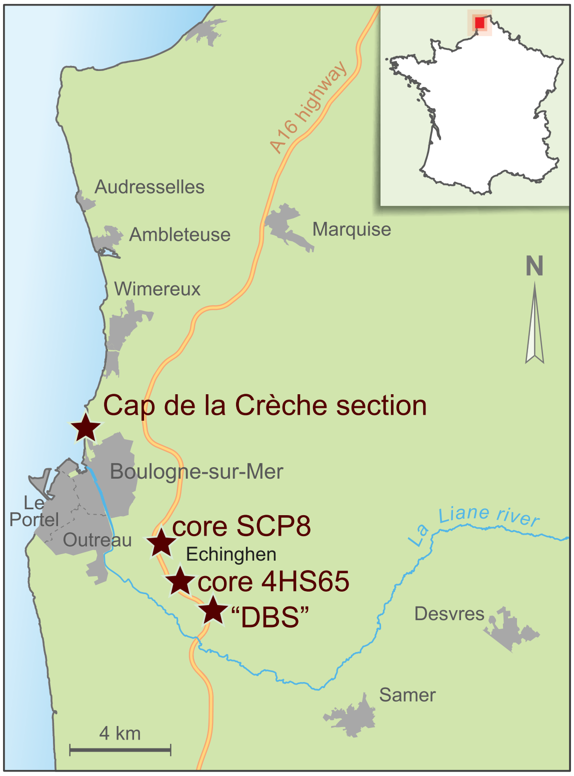

Figure 2. Studied sites for organic matter content in the Boulonnais, France, near the coastal town of Boulogne-sur-Mer. "DBS" is for Diffuseur de Boulogne Sud.

Mer (Cap de la Crèche outcrop, Figure 2), showing deposits from the upper part of the *Mutablis* zone in the late Kimmeridgian (only one metre within this later zone cropping out) onto the *Kerberus* zone in the late Tithonian [Proust et al., 1995]. Mostly shallow, inner platform facies of late Oxfordian and early Kimmeridgian ages are not cropping out nowadays. During the winter 1996, the A16 motorway works allowed observation of the lowermost formations of the Kimmeridgian in the vicinity of Boulogne-sur-Mer. The so-called Oolithe d'Hesdin-l'Abbé, Caillasses d'Hesdigneul and Calcaires de Brecquerecque, as well as the base of the Argiles du Moulin Wibert formations (Figures 3 and 4) were visible for several months before the trench was paved (Diffuseur de Boulogne Sud (DBS) outcrops, Figure 2). Moreover, several cores were drilled for geotechnical purpose. One of them, the SCP8 core (Figure 2), covering the upper Oxfordian–lowermost Kimmeridgian interval, from the Argiles du Mont des Boucards to the Caillasses d'Hesdigneul formation was intensely studied [Schnyder et al., 2000]. The 4HS65 core completes this local stratigraphy, showing the upper part of the Calcaires de Brecquerecque and the base of the Argiles du Moulin Wibert formations (Figures 2 and 3).

The DBS is located just after the place where the A16 motorway crosses the Liane River and 2 km before the toll (Figure 2). The outcrops were studied during the road works along a 500 m-long trench. The two studied cores, SCP8 and 4HS65, are located near the village of Echinghen (Figure 2). Both penetrated the sedimentary deposits over 50 m and 38 m, respectively. The uppermost part of the Argiles du Moulin Wibert was sampled using the Cap de La Crèche outcrop (Figure 2). The stratigraphic extent of each outcrop and core that helped construct the composite log are indicated in Figures 3 and 4.

After detailed sedimentological field observations, the 4HS65 core and the outcrops were sampled at high resolution with a sampling step ranging from 5 to 20 cm. Note that there are some out-

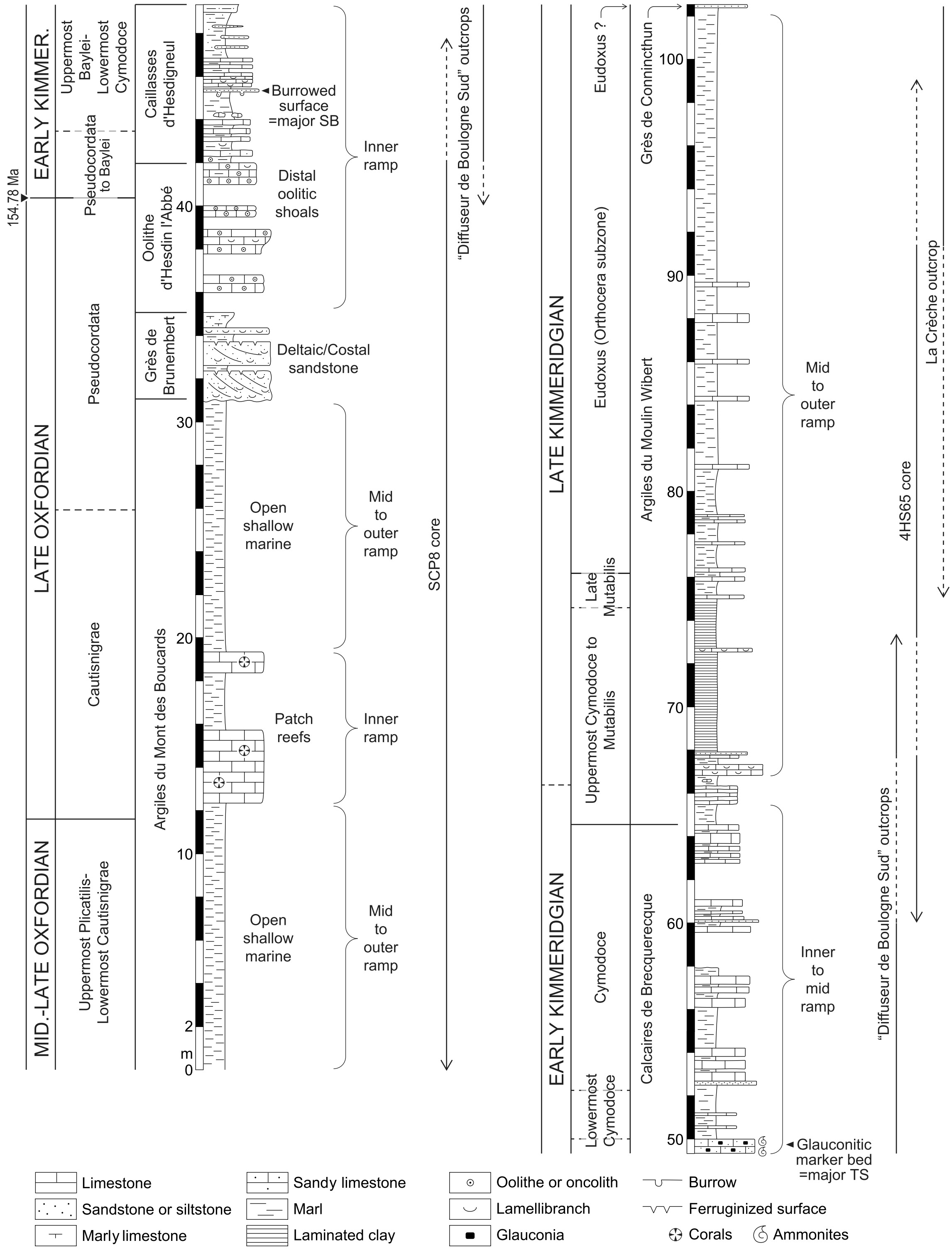

Figure 3. Composite log at the Oxfordian–Kimmeridgian transition in the Boulonnais, France.

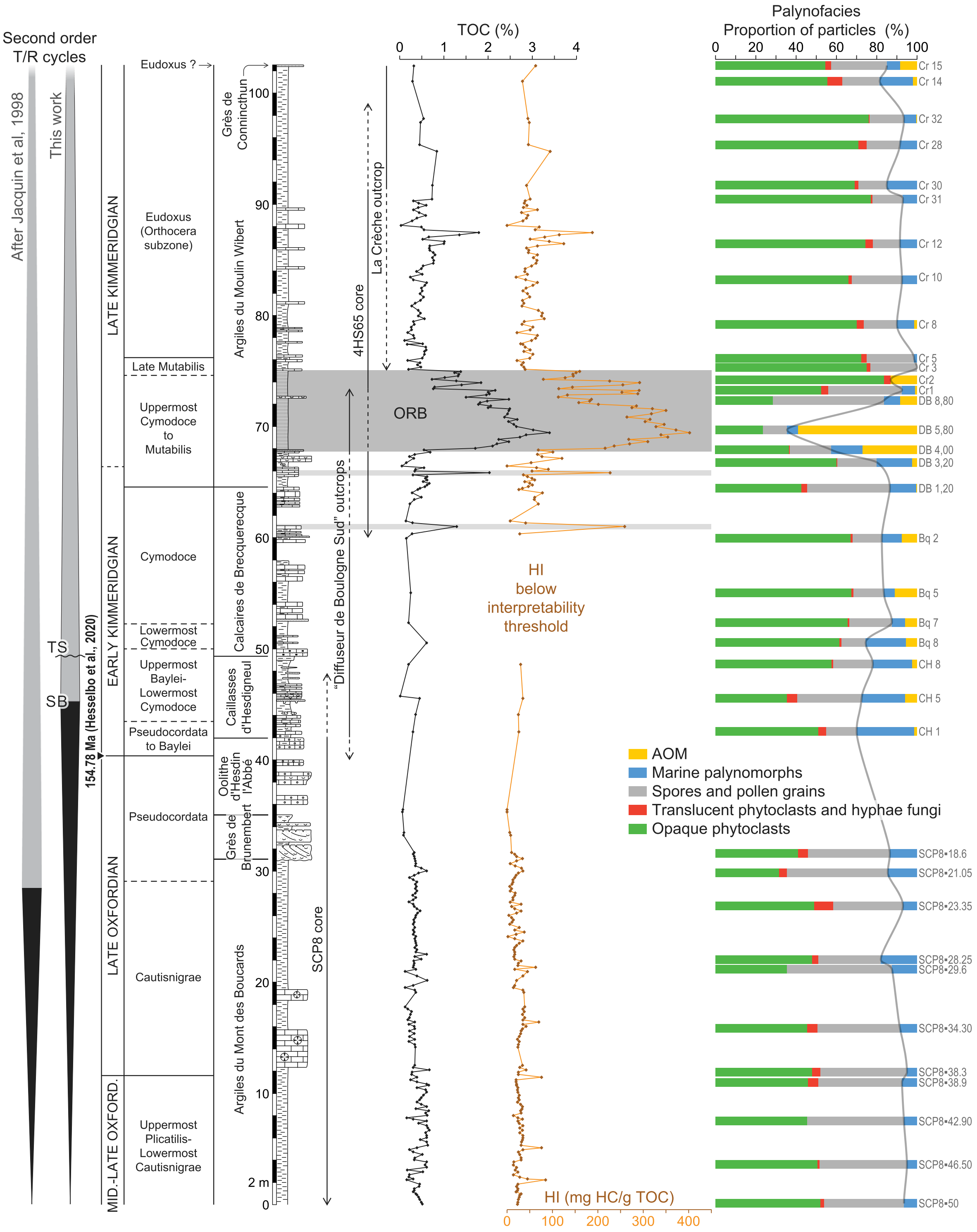

Figure 4. Rock-Eval pyrolysis and palynofacies data against the composite log at the Oxfordian–Kimmeridgian transition in the Boulonnais, France. Note the major organic-rich interval evidenced during the Late *Cymodoce* to late *Mutabilis* zones interval (Early Late Kmmeridgian).

crop gaps (a few decimetres in thickness) on the DBS outcrops. The sedimentary organic matter was characterised using Rock-Eval pyrolysis and palynofacies observations. Facies description, biostratigraphy, Rock-Eval pyrolysis (142 samples) and palynofacies (11 slides) data from SCP8 core have been published in Schnyder et al. [2000] (Figure 4). Additional, newly presented data correspond to 152 samples for Rock Eval pyrolysis and 25 samples for palynofacies slide preparation collected in the DBS outcrops, 4HS65 core and the Cap de la Crèche outcrop (Figure 4). A total of 10 slides were selected among these 25 slides for palynology to help dating the Caillasses d'Hesdigneul, Calcaires de Brecquerecque, and base of Argiles du Moulin Wibert formations. All the above mentioned results, are shown in Figures 3 and 4, in order to present an integrated organic matter dataset at the Oxfordian–Kimmeridgian transition, based on a total of 294 Rock-Eval pyrolysis analyses and 36 palynofacies slides.

Calcium carbonate content was determined using the 152 new samples with a carbonate bomb, and the total carbon content was determined using a LECO WR-12 analyser. Total organic carbon (TOC) content was calculated by determining the difference between total carbon and carbonate carbon, assuming that all carbonate is pure calcite. The source and thermal maturation of the organic matter were estimated using a Rock-Eval instrument using an Oil Show Analyser device [Espitalié et al., 1986]. Standard notations are used: Tmax is expressed in °C; TOC content in weight % and hydrogen index (HI = S2/TOC × 100) in mg HC per g of TOC.

Organic residues were obtained using a standard palynological treatment with HCl-HF maceration to remove the mineral fraction [Steffen and Gorin, 1993]; no oxidation by nitric acid was used. The residues were sieved (10 μm) and directly mounted for palynofacies observations. The classification used is a simplified version of that detailed in McArthur et al. [2016] and Schnyder et al. [2017]. Five constituents categories are retained (Figure 4), which will be used in the diagram illustrating the results. These categories are the amorphous organic matter (AOM), which is generally considered in marine settings as derived from algal–bacterial marine production, the marine palynomorphs (including here dinoflagellate cysts, foraminera linings, and scolecodont remains), the spores and pollen grains, the translucent phytoclasts and the opaque phytoclasts (the latter two derived from terrestrial plants tissues) (see McArthur et al. [2016] and Schnyder et al. [2017] for more details). Palynostratigraphic slides for dinoflagellate identifications were prepared from the organic residues, after a slight oxidation by nitric acid and heavy mineral separation. Ten samples were studied for dinoflagellate identifications, 3 from the Caillasses d'Hesdigneul, 2 from the Calcaires de Brecquerecque, and 5 from the Argiles du Moulin Wibert.

3. The upper Oxfordian and lower Kimmeridgian succession of the Boulonnais

3.1. *Facies and long-term sea-level sequences*

From the mid-Oxfordian up to the early late Kimmeridgian, the sedimentary record from the Boulonnais corresponds to marine deposits with mixed carbonate/siliclastic lithologies and interpreted to be inner to outer ramp (platform) deposits. In ascending order, six successive formations have been described: the Argiles du Mont des Boucards, the Grès de Brunembert, the Oolithe d'Hesdin-l'Abbé, the Caillasses d'Hesdigneul, the Calcaires de Brecquerecque and finally the Argiles du Moulin Wibert formations (Figures 3 and 4). The Argiles du Mont des Boucards Formation is 15–30 m thick and corresponds to homogeneous claystone to marlstones with some mollusc shell layers (*Ostrea*) interpreted to be mid-to-outer ramp deposits. It locally contains patch-reef facies in its middle part (Calcaire de Brucquedal Member) corresponding to inner ramp deposits. The following Grès de Brunembert Formation is 1–10 m thick and consists of bivalves and locally gastropod-rich sandstone beds alternating with silty to sandy marls. These deposits are interpreted to be deltaic/coastal sandstones. The Oolithe d'Hesdin-l'Abbé Formation consists of 6–10 m thick whitish bioturbated poorly-sorted oolitic and oncolitic limestones passing to marls with oolites and is interpreted to be inner ramp, distal oolitic shoals. The Caillasses d'Hesdigneul Formation is 5 m thick and starts with black marls containing oolites and some oysters, passing upward to oolitic sandy limestones with gastropods (*Harpagodes*) and sea-urchins and then to micritic limestones, mostly devoid of fauna. The topmost beds are usually covered by hard-grounds, with eroded surfaces and small oyster encrustations. The depositional environment is interpreted to be an inner ramp, lagoonal facies. Compared with the underlying Argiles du Mont des Boucards Formation, the Grès de Brunembert, Oolithe d'Hesdin l'Abbé and Caillasses d'Hesdigneul formations evidence a shallowing-up trend at the Oxfordian/Kimmeridgian boundary (Figures 3 and 4). The following Calcaires de Brecquerecque Formation shows a 15 m thick alternation of marls and limestones, containing thin sand to sandstone layers. The faunal content is dominated by bivalves, sea-urchins, and brachiopods, but devoid of ammonites. A peculiar (0.5 m thick) sandy and glauconitic limestone, rich in ammonites, is visible at the base of the formation (Figure 3). This observation suggests an important transgressive event with erosional surfaces, glauconite accumulation, and ammonite condensation or reworkings at the base of the Calcaires de Brecquerecque (Figure 3). The depositional environments in the Calcaires de Brecquerecque are interpreted to be inner to mid-ramp deposits, and a deepening-up trend is obvious with respect to the underlying Caillasses d'Hesdigneul Formation (Figures 3 and 4). The following Argiles du Moulin Wibert Formation directly overlies the Calcaires de Brecquerecque. The formation as seen in the Cap de la Crèche section is around 20 m thick [Mansy et al., 2000], however, the base of the formation is lacking in Cap de la Crèche and the whole thickness reach up to 38 m adding the DBS outcrop sedimentary sequences (Figure 3). The Argiles du Moulin Wibert Formation shows an alternation of gray to black marl and limestone beds, often rich in bivalves [*Nanogyra virgula*, *Trigonia* and *Gervillia*, Mansy et al., 2000]. The dark clays are remarkably laminated between 68 and 75 m (composite section, Figure 3). The Argiles du Moulin Wibert correspond to mid to outer ramp deposits that again mark a deepening-up trend with respect to the underlying Calcaires de Brecquerecque Formation, from the early Kimmeridgian to the base of the late Kimmeridgian (Figures 3 and 4). The Argiles du Moulin Wibert is finally overlain by the Grès de Connincthun Formation (Figure 3).

To summarise, the sedimentary succession of the Boulonnais, from the mid-Oxfordian up to the early late Kimmeridgian, corresponds to two open marine, deeper marl-dominated intervals (i.e. Argiles du Mont des Boucards and Argiles du Moulin Wibert) separated by a shallower marine, sandstone to carbonate platform-dominated interval (comprising the Grès de Brunembert, the Oolithe d'Hesdin l'Abbé, the Caillasses d'Hesdigneul and the Calcaires de Brecquerecque), the latter interval being deposited at around the Oxfordian/Kimmeridgian boundary (Figures 3 and 4). A long-term, second-order relative sea-level regressional and then transgressional trend (T/R cycle) can thus be evidenced in the Boulonnais, with a second order sequence boundary that can be placed at the major hardground in the Caillasses d'Hesdigneul at 45.5 m (uppermost *Baylei*–lowermost *Cymodoce*) and a major transgressive surface corresponding to the glauconitic ammonite-rich marker-bed at 49.5 m (lowermost *Cymodoce*) (Figures 3 and 4). These relative sea-level trends are equivalent to the regressive part of the second-order cycle 8 and the transgressive part of second-order cycle 9, as referred to by Jacquin et al. [1998] at the scale of Western Europe, with a slight difference in the position of the major sequence boundary (Figure 4).

3.2. *Biostratigraphy*

Age determination of the Argiles du Mont des Boucards in the Middle-late Oxfordian until the Argiles du Moulin Wibert in the late Kimmeridgian is based on ammonite and dinocyst distributions [Dutertre, 1925, Debrand-Passard et al., 1980, Mansy et al., 2000, Schnyder et al., 2000, see Figures 3 and 4]. A summary of biostratigraphic information for each formation, based on published data, is provided in the Supplementary Data File. To complete the published data set in some poorly-dated intervals, we performed new dinocyst identification using 10 samples collected in the Caillasses d'Hesdigneul, Calcaires de Brecquerecque and Argiles du Moulin Wibert formations. These new dinocyst identifications are presented in the Supplementary Data File, and the corresponding results are integrated into the biostratigraphic framework as shown on Figures 3 and 4.

4. Organic geochemistry and palynofacies results

The average Tmax value from the Rock-Eval in the entire set of data is 424 °C. This indicates an immature organic matter, which was not affected by significant burial diagenesis and is therefore suitable for palaeoenvironmental studies [Espitalié et al., 1986].

The Rock-Eval and palynofacies results allow distinction between three parts in the composite log with respect to the organic matter content.

The first interval extends from 0 to 68 m, including the middle-late Oxfordian to early Kimmeridgian deposits, from the Argiles du Mont des Boucards to the Calcaires de Brecquerecque formations (Figure 4). TOC values are mainly below 1 wt% (TOC = 0.38 wt% on average) and HI values mainly below 100 mgHC/gTOC (HI = 30 mgHC/gTOC on average). These results are represented as grey dots on Figure 5, and correspond to a Type III organic matter, probably deriving from terrestrial debris and/or from a relatively degraded marine organic matter and even Type IV organic matter (highly degraded organic matter whose origin cannot be assessed). The palynofacies from this interval show a dominant terrestrial component of 84% of the total assemblage (defined here as opaque+translucent debris+spores and pollen grains+hyphae from fungi) over a marine component of 16% (defined as AOM+dinoflagellate cysts+foraminifera linings) (Figure 4). These results are in line with those from the Rock-Eval pyrolysis and suggest a mixture of a relatively degraded marine organic matter and strong terrestrial organic influx from the neighbouring emerged lands (Figure 1). Low TOC and IH values and the dominant terrestrial component in palynofacies suggest a moderate or low palaeoproductivity and that the water masses were most probably well oxygenated. An interesting secondary feature is the significant increase in marine palynomorph (dinoflagellate cysts and foraminifera linings) proportions from sample CH1 (42.6 m) to sample Bq8 (50.6 m) within the Caillasses d'Hesdigneul and the base of the Calcaires de Brecquerecque (Figure 4). Marine palynomorph proportions in the total assemblage are comprised between 20 and 28.5% within this stratigraphic interval, whereas marine palynomorph proportions are always below 20% and often below 10% in the other palynofacies samples from our data set. This suggests that periodic planktonic blooms occurred during the deposition of the shallow marine to lagoonal Caillasses d'Hesdigneul and base of Calcaires de Brecquerecque formations.

The second interval extends from 68 to 75 m. It includes a time interval spanning the uppermost *Cymodoce* onto the late *Mutabilis* zones in early late Kimmeridgian, and correspond to the darker, laminated marls well observed at the base of the Argiles du Moulin Wibert Formation deposits (Figure 4). TOC values are largely higher when compared to the first interval, being mainly above 1.5 wt% (TOC = 2 wt% on average) and reaching up to 3.4 wt%. HI values are higher as well, being often above 200 mgHC/gTOC (HI = 244 mgHC/gTOC on average), and reaching up to 402 mgHC/gTOC. These results suggest a Type III to Type II organic matter deposition, the latter most probably deriving from marine organic matter sources, such as planktonic/bacterial materials [Tyson, 1995]. These analyses correspond to the black dots on Figure 5 and the organic-rich interval II will be referred to as "Organic Rich Bands, ORB" in the following. Interestingly, the TOC and HI curves are asymmetric in shape (Figure 4), meaning that there is a sudden increase in TOC and HI values up to a maximum from 68 to 69.75 m, and then a progressive decline in TOC and HI values from 69.75 m to 75 m. The palynofacies from this second interval show a terrestrial component of 71% on average, and a correlative marine component of 29% on average, e.g., an elevated average value compared to our first interval between 0 m and 68 m. The two samples located between 68 and 69.75 m and associated with the sharp TOC increase discussed above, show an even lower terrestrial component and an higher marine component in the palynofacies (64% and 36% respectively on average, Figure 4). This indicates that the peak in TOC and HI values corresponds to a peak of marine components in palynofacies. Both palynofacies and Rock-Eval results thus attest to a mixture of Type III (derived from terrestrial plant debris) and Type II (derived from marine planktonic and/or bacterial production) organic sources during deposition of the second interval, with a large increase in production from marine sources and better preserved organic matter. This indicates enhanced primary productivity in surface waters and/or occurrence of dysoxia to anoxia in water masses during the uppermost *Cymodoce* and part of the *Mutabilis* zones in the Boulonnais area corresponding to the organic-rich interval labelled "C" in Figure 6. In more detail, it seems that this organic-rich interval C is

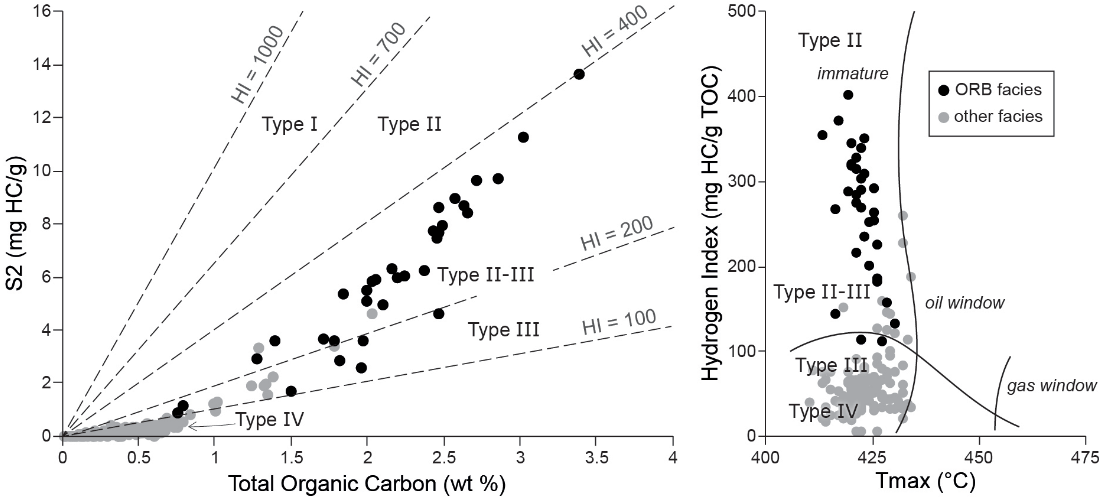

Figure 5. S2/TOC and HI/Tmax from the Oxfordian–Kimmeridgian boundary samples in the Boulonnais. Note the sharp contrast between ORB samples (black dots) and non-ORB samples (grey dots).

announced by two peaks in TOC and HI values centered around 61 m and 65.90 m, TOC reaching up to 1.29 wt% and 2.03 wt% and HI values reaching up to 259 mgHC/gTOC and 227 mgHC/gTOC, respectively, and labelled "A" and "B" in Figure 6. We interpret these peaks as indicating first, short-term phases of increasing marine productivity and/or better preservation of organic matter linked to periodic dysoxia/anoxia development in water masses during the uppermost *Cymodoce* to lowermost *Mutabilis* zone (Figure 6 and Supplementary Data), preceding the deposition of the main organic-rich interval. Furthermore, palynofacies data also evidence a slight increase in marine palynomorph proportions from sample DB1.20 (64.5 m) to sample DB4 (68 m) (Figure 4). Marine palynomorph proportions are comprised between 13 and 17.5% within these samples. This slight increase again predates the major organic-rich interval beginning at 68 m and corresponds to the interval of TOC and HI peaks located in the uppermost *Cymodoce* to the lowermost *Mutabilis* zones. These data most probably evidence planktonic blooms linked to increasing periodic marine influences.

The third interval extends from 75 to 102.50 m, and includes the uppermost *Mutabilis* to *Eudoxus* (*Orthocera* subzone) zones in the late Kimmeridgian, in the upper part of the Argiles du Moulin Wibert and the base of the Grès de Connincthun formations (Figure 4). TOC values are again mainly below 1 wt% (TOC = 0.5 wt% on average) and HI mainly below 100 mgHC/gTOC (HI = 53 mgHC/gTOC on average), similar to what was observed in the first interval between 0 m and 68 m. These results point to a Type III organic matter, and again correspond to the grey dots on Figure 5. The palynofacies indicate a dominant terrestrial component (91% of the total assemblage) over the marine component (9%), a feature again quite similar to the first interval. The organic matter is thus a mixture of strong terrestrial organic sources and oxidized marine sources. The primary productivity levels in surface waters were certainly low or moderate and the water masses rather well oxygenated. Of special interest is a clear increasing trend in TOC and HI values from 78 to 87.50 m in the Argiles du Moulin Wibert in the *Eudoxus* zone, TOC values reaching up to 1.79 wt% and HI reaching up to 188 mgHC/gTOC (Figure 4). This probably correspond to a moderate increase of marine organic matter production and/or preservation. However, this minor trend is not reflected in the palynofacies data by an increase of the marine organic particles (Figure 4). It may be possible that this trend toward higher TOC values should be followed higher up by a symmetric decreasing trend in TOC, from 87.5 m onto the base of the Grès de Connincthun deposition, evidencing a flat-shaped organic cycle (Figure 4). However, the low resolution of our data set above 90 m does not allow us to ascertain this possibility.

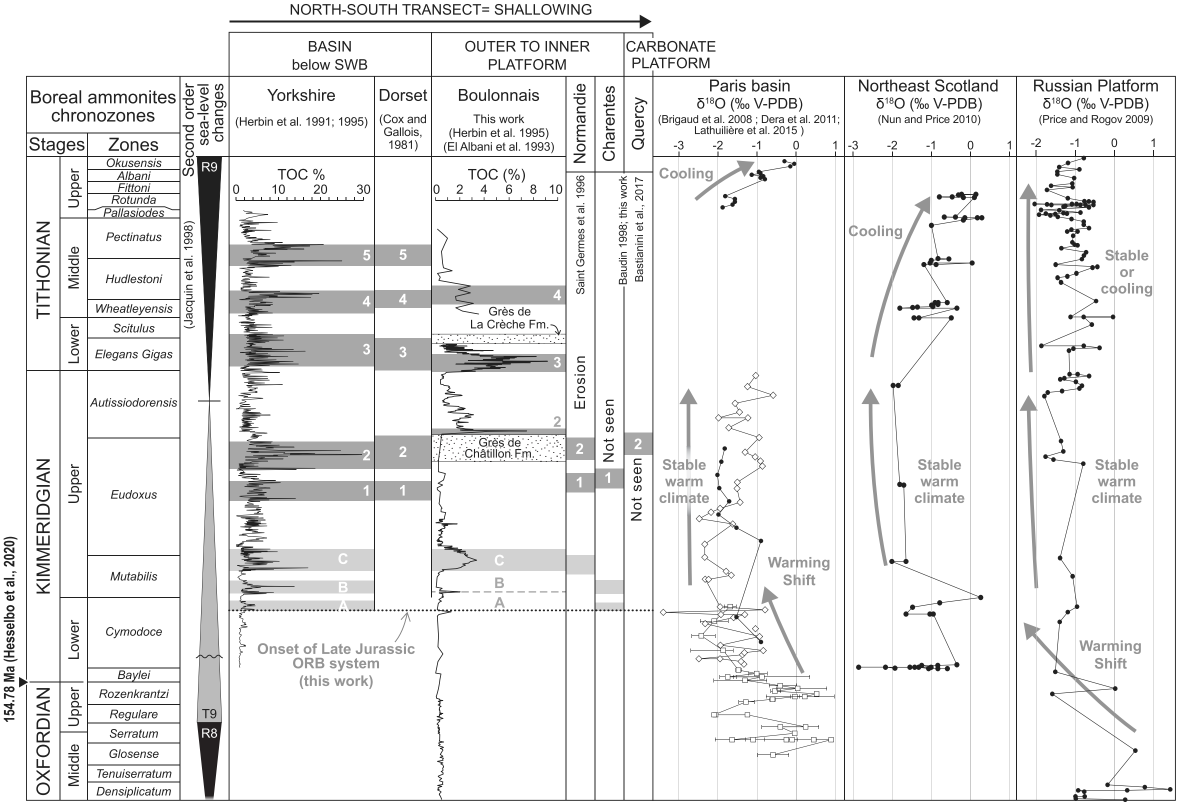

Figure 6. Late Jurassic organic matter enrichments in Yorkshire and Dorset in the UK (basinal facies), and Boulonnais, Normandy, Charentes and Quercy in France (platform facies), showing the simultaneity of ORB system onset (Uppermost *Cymodoce* to late *Mutabilis* zones interval), and the relatively good correlations of the various ORB at large scale. Note (1) the corresponding shift toward warmer climates at the onset of ORB deposition, (2) the association of the ORB system with stable, warm climates and (3), the termination of the ORB system in NW European basins as a large-scale cooling trend is obvious during the middle part/upper part of the Tithonian. Isotopic data from the Paris Basin: white squares after Brigaud et al. [2008] and Lathuilière et al. [2015]; black dots after Dera et al. [2011].

5. Discussion

Significant organic matter enrichments, respectively labelled "A", "B" and "C" (see Figure 6) occur at the topmost part of the Calcaires de Brecquerecque and the base of the Argiles du Moulin Wibert Formation in the Boulonnais, in the uppermost *Cymodoce* and *Mutabilis* zones, at the early/late Kimmeridgian boundary, with TOC reaching up to 3.4 wt% and HI values up to 400 mgHC/gTOC. Marine organic matter planktonic algal/bacterial production was enhanced and/or dysoxia/anoxia did occurred in water masses. This organic matter accumulation strongly contrasts with the underlying middle-late Oxfordian to early Kimmeridgian time interval in the same region, were TOC values are always low to very low and below 1 wt% (Figure 4).

5.1. *Comparison with Normandy, Charentes and Quercy (France)*

In the neighbouring Normandy area (4, Figure 1), the organic matter analyses [Baudin, 1992, Saint-Germès et al., 1996] reveal a low content of organic carbon (<0.5%) in lower Kimmeridgian deposits (*Baylei* and *Cymodoce* zones), whereas the total organic carbon content varies between 1 and 7% in upper Kimmeridgian sediments (*Mutabilis* and *Eudoxus* zones).

The HI-values indicate a recycled and oxidized terrigenous material in lower Kimmeridgian marls and limestones, whereas more or less oxidized marine organic matter dominantly occurs in upper Kimmeridgian black shales. Three organic-rich bands are recognised within the Argiles d'Octeville Formation. The oldest is located in the Argiles du Croquet Member (*Mutabilis* subzone), whereas the others two are from the *Eudoxus* zone. The first one lies in the middle part of the Argiles d'Ecqueville Member (*Orthocera* subzone) and the latest in the upper part of the Argiles d'Ecqueville Member (*Contejeani* subzone). Although the biostratigraphic resolution of the Kimmeridgian is poor in the Boulonnais area, the major organic-rich band from the base of the Argiles du Moulin Wibert (labelled C) seems coeval with the organic-rich band from the Argiles du Croquet Member (Figure 6). The similar evolution of palynological and organic geochemical features observed between Normandy and Boulonnais suggest a common event. This implies a late *Mutabilis* subzone dating for this organic-rich band observed in the two regions (Figure 6), although we have seen that in the Boulonnais, first, older short-lived organic enrichments ("A" and "B", Figure 6) are obvious in the uppermost *Cymodoce*/lowermost *Mutabilis* zones. The Argiles du Moulin Wibert coincide with a major change in lithology (e.g. from dominantly carbonates to dominantly claystones), similar to that occurring at the base of Argiles d'Octeville, both indicating a deepening-up, long-term transgressive trend at the boundary between the early and late Kimmeridgian, beginning in the earliest Kimmeridgian, as revealed by the facies succession described in the Boulonnais (Figure 4).

In the Charentes area (5, Figure 1), organic enrichment intervals are obvious in the upper part of the *Cymodoce* zone, TOC values being above 2 wt% and HI above 400 mgHC/gTOC [Figure 6, Baudin, 1998, this work]. Two other organic-rich intervals are recorded in the *Mutabilis* zone and in the *Eudoxus* zone (*Orthocera* subzone) zone (Figure 6).

In Quercy (6, Figure 1) organic rich intervals are recognized only in the upper part of the *Eudoxus* zone and the basal part of the *Autissiodorensis* zone, TOC values reaching up to 15 wt% and IH values up to 700 mgHC/gTOC, and palynofacies are dominated by AOM within these levels, indicating a dominant marine organic source with enhanced palaeoproductivity and/or dysoxia/anoxia [Figure 6, Baudin, 1998, Bastianini et al., 2017; this work].

5.2. *Onset of late Jurassic organic rich bands (ORB) in NW European margin*

The study of the Kimmeridge Clay Formation in the Cleveland Basin in Yorkshire (UK) has evidenced the cyclic nature of marine organic matter distribution, from primary organic fluctuations less than 1 m in thickness to decametre-thick organic-rich intervals [Herbin et al., 1991, 1995, Herbin and Geyssant, 1993]. Five main concentrations of oil shales with TOC higher than 10 wt%, which can be correlated throughout several cores in Yorkshire in late Kimmeridgian and early Tithonian beds, have been defined as "organic belts" by Herbin et al. [1991, 1993]. They correspond to periods highly favourable for marine organic matter production and preservation, and alternate with unfavourable periods [e.g., most of the *Autissiodorensis* zone, the *Scitulus* zone, middle part of the *Hudlestoni* zone and the top of the *Pectinatus* zone, Herbin et al., 1991, 1993]. Similar organic-rich intervals found in subsurface data in Dorset in the UK were previously described as "organic rich bands" (ORB) [Cox and Gallois, 1981] and have been recognized in outcrops in Dorset as well [Huc et al., 1992]. The five ORB can indeed be correlated from Yorkshire to Dorset and are recognised: in the middle part of the *Eudoxus* zone (ORB1), in the upper part of the *Eudoxus* zone and the lower part of the Autissiodorensis zone (ORB2), in the *Elegans* zone (ORB3), in the upper part of the *Wheatleyensis* zone and the basal part of the *Hudlestoni* zone (ORB4) and finally in the upper part of the *Hudlestoni* zone and the lower part of the *Pectinatus* zone (ORB5), spanning the late Kimmeridgian to part of the late Tithonian time-interval (Figure 6). In Yorkshire, TOC from the ORB are commonly above 5–10 wt% and can reach up 30 wt%, whereas HI values are often above 400–500 mgHC/gTOC and can reach maxima of 800 mgHC/gTOC [Herbin et al., 1991, 1995], pointing mostly to a well-preserved Type II marine organic matter deposition associated with probable dysoxia/anoxia during ORB deposition. No significant organic matter enrichments are observed in beds younger than the *Pectinatus* zone (early Tithonian). The above described ORB can be correlated throughout the Boulonnais area in France [Herbin and Geyssant, 1993], but only the upper part of ORB2 in the Autissiodorensis zone, the lower part of ORB3 in the *Elegans* zone, and the ORB4 in *Wheatleyensis* and *Hudlestoni* zones are recorded (Figure 6). Furthermore, TOC and HI values are often lower in the Boulonnais when compared to the similar Yorkshire and Dorset intervals, reaching up to 9 wt% and 560 mgHC/gTOC respectively in the Argiles de Châtillon Formation (*Elegans* zone) [El Albani et al., 1993, Herbin et al., 1995]. This has been related to the shallower environments of the Boulonnais, corresponding to outer to inner ramp-type platforms neighbouring emerged lands [Proust et al., 1995, Figure 1], when compared to the deeper, more basinal and often below storm wave base environments of the Kimmeridge Clay Formation in UK [Herbin et al., 1995]. Shallower and nearshore environments in the Boulonnais may have been associated with better oxygenated waters, whereas dysoxia/anoxia could have persisted in deeper environments [Creaney and Passey, 1993, Herbin et al., 1995]. Although, regressive trends may have led in nearshore environments to the deposition of thick sandstone packages not prone to organic matter deposition and even eroding older deposits, such as the Grès de Châtillon and Grès de la Crèche in the Boulonnais [Herbin et al., 1995, see Figure 6]. Furthermore, ORB1 and ORB2 can be partly recognised in Normandy, Charentes and Quercy (Figure 6).

As stated above, our data at the Oxfordian/Kimmeridgian transition in the Boulonnais, compared with that of Normandy, Charentes and Quercy [Baudin, 1992, Saint-Germès et al., 1996, Baudin, 1998, this work] show that a major organic-rich matter interval can already be identified in the (probably late) *Mutabilis* zone (C, Figure 6). Re-interpreting the Rock-Eval data from Herbin et al. [1991, 1995] in Yorkshire, it is remarkable that two significant organic-rich accumulations can be identified in the *Mutabilis* zone, at the base and at the top of the *Mutabilis* zone, respectively (Figure 6), although Herbin and Geyssant [1993] did not define "organic belts" within the *Mutabilis* zone. Those two stratigraphic intervals yield TOC comprised between 2–5 and more than 10 wt%, and HI values comprised between 400 and 600 mgHC/gTOC [Herbin et al., 1995, Figure 6]. Furthermore, a first TOC peak occurs in the late *Cymodoce* zone (Figure 6). We thus propose that these first organic matter enrichments in the late *Cymodoce* and *Mutabilis* stratigraphic intervals are lateral equivalents to those seen in the Boulonnais and labelled "A", "B" and "C" respectively, and also partly recognised in Normandy and Charentes (Figure 6). Therefore, the onset of the Late Jurassic ORB system of the Kimmeridgian Clay Formation and lateral equivalents in France may have been located in the late *Cymodoce–Mutabilis* stratigraphic intervals, at around the early/late Kimmeridgian boundary, and not higher up in the *Eudoxus* zone, as previously stated (Figure 6). This hypothesis is in accordance with faintly bituminous mudstones with *Aulacostephanus eulepidus* in the Black Head section of Dorset [Cox and Gallois, 1981]. As is widely observed in younger strata, maxima of TOC and HI values in the *Mutabilis* zone in the Boulonnais (3.4 wt% and 400 mgHC/gTOC, respectively) are lower that the ones in Yorkshire (above 10 wt% and 600 mgHC/gTOC, respectively) and only the upper *Mutabilis* zone organic-rich interval is well recorded in the Boulonnais and Normandy. This was again probably related to the nearshore environments deposited in Normandy and the Boulonnais, less prone to organic matter preservation when compared to deeper, basinal environments. Therefore, the late Jurassic ORB system in NW Europe would have had a duration of around 6.8 Myr (GTS 2021), starting at the topmost part of *Cymodoce* zone and ending around the top of *Pectinatus* zone (Figure 6).

5.3. *Palaeoenvironmental and palaeoclimatic controls on ORB onset and deposition*

Herbin et al. [1991, 1993, 1995] suggested that transgressions were one of the main driving factors for marine organic matter accumulation in the Kimmeridge Clay Formation, as the five ORB correlate well with deepening trends. They however also remarked that all transgressive trends during the late Jurassic did not led to organic-rich beds, indicating that sea-level variations were not the only controls on organic matter enrichments. Our data from the Boulonnais at the Oxfordian–Kimmeridgian transition support this hypothesis, as the first significant organic enrichment found in the Argiles du Moulin Wibert Formation occur at the onset of a long-term "second-order" transgressive trend [Jacquin et al., 1998] that led in the Boulonnais to the flooding of the late Oxfordian carbonate platforms (Figures 5 and 6). The end of the ORB system after the *Pectinatus* zone also corresponds to a long-term shallowing-up trend in NW European basins [Jacquin et al., 1998, see Figure 6], accelerating during the late Tithonian, that will lead locally to widespread emersion and/or widespread shallow marine or non-marine deposits (e.g. the so-called Purbecks beds).

Tyson et al. [1979] additionally proposed that the peculiar physiography of the late Jurassic NW European shelf also played a role in the widespread organic-rich matter enrichments as seen in the Kimmeridge Clay Formation. The rapid drowning of the large shallow and flat, carbonate-dominated NW European shelf that existed during the late Oxfordian–early Kimmeridgian would have separated the mixed, well oxygenated surface waters from the sea bottom, initiating water stratification and creating stagnant, anaerobic layer(s), favourable for organic matter preservation [Tyson et al., 1979]. These stagnant water bodies were probably relatively isolated from the oceanic tethyan waters to the south, inhibiting large-scale water mixing [Tyson et al., 1979]. Our work in the Boulonnais shows that the ORB deposition, initiated at the early/late Kimmeridgian boundary, occurred at the very early phases of the long-term transgression and the related late Jurassic platform drowning (Figure 6), as the area was probably only covered by a relatively shallow water. This shows that an efficient system for production and/or preservation of organic matter did exist and formed quickly in relatively shallow water, proximal areas. However, the better preservation of organic-rich intervals and the higher content in organic matter in lateral, deeper facies of Yorkshire (Figure 6) also point out that the production and preservation mechanism(s) of organic matter were more efficient in basinal settings at the onset of the ORB system, as shown previously for the five ORB previously described [Herbin et al., 1991, 1993].

Following Dunn [1974] and House [1985], who had previously investigated the orbital forcing of climate as a control on sedimentary deposits in the Kimmeridge Clay Formation, Herbin et al. [1991, 1995] recognized the cyclic nature of the organic matter accumulation in the Kimmeridge Clay Formation, this being observed from millimetre-scale cycles up to decametre-thick cycles and suggesting a climatic control on organic matter cycles. Studying palynofacies data in the Kimmeridge Clay Formation in Dorset, Waterhouse [1995] evidenced the occurrence of obliquity and precession orbital forcing on palaeoenvironmental variations within cycles. Using trace element data, Tribovillard et al. [1994] evidenced the local development of reducing conditions enhancing organic matter accumulation in the Kimmeridge Clay Formation in Yorkshire, but also stressed that phytoplanktonic production was an important factor—if not the main factor—in organic matter accumulation, a conclusion backed by Bertrand et al. [1994]. Indeed, phytoplanktonic production may be driven, directly or indirectly by climatic fluctuations [Tyson, 1995].

Interestingly, the onset of the late Jurassic ORB at the early/late Kimmeridgian boundary as shown in this work is contemporaneous to a large-scale (global?) climate warming that can be evidenced in the Paris Basin [Brigaud et al., 2008, Dera et al., 2011, Lathuilière et al., 2015], in Scotland, UK [Nunn and Price, 2010] and in the Russian Platform [Price and Rogov, 2009] using oxygen isotopes measured on mollusc or belemnite fossils (Figure 6). All these records show an isotopic shift of around 2‰ toward more negative values, beginning in the middle-late Oxfordian (*Regulare* zone in the Paris Basin) and ending with the more negative values at around the early/late Kimmeridgian boundary (in the top *Cymodoce* or the *Mutablis* zone in the Paris Basin, see Figure 6). Interpreted in term of palaeotemperature changes, this would correspond to a sea-water warming as high as 6 °C during this stratigraphic interval [Brigaud et al., 2008]. Zuo et al. [2019] similarly evidenced a warming trend during the Kimmeridgian in the Lower Saxony Basin (Germany). Using clumped isotope analyses, Wierzbowski et al. [2018] showed that at least a part of the recorded isotopic shift in the early late Kimmeridgian in the Russian Platform may have been due to a salinity decrease, rather than to a temperature change. According to Wierzbowski et al. [2018], enhanced freshwater flows were associated with low sea level and a relative isolation of the Russian Platform, leading to water mass stratifications, ultimately promoting black shales deposition. Indeed, salinity fluctuations in water masses, due to climate changes and/or sea-level fluctuations are known to locally enhance water stratification and organic matter accumulation, as was evidenced in the Late Tithonian/Berriasian lagoonal facies from the so-called Purbeck Beds of Dorset, UK [Schnyder et al., 2006, 2009] for example. As stressed above, we do think that such stratification processes in shallow, restricted water mass may have favoured, locally, the early record of ORB deposits in NW Europe. It is quite clear that salinity fluctuations through time in marine basins are currently under-estimated, and further studies are urgently required on this topic. However, the late Jurassic warming parallels the long-term late Oxfordian–early Kimmeridgian sea-level rise in the French and British Basins (Figure 6). Such a long-term sea-level rise would certainly not have been associated with a widespread and long-term increase in freshwater inputs. We therefore suggest that climate was an additional major, long-term control on the ORB onset, the general (global) warming at the early/late Kimmeridgian boundary possibly leading to an abrupt increase in phytoplanktonic productivity levels in the epeiric seas that were initiated by the sea-level rise. Oxygen isotope curves appear then to be mostly stable until the top of the *Autissiodorensis* zone, suggesting continuing warm conditions, favourable for primary production in surface waters, during most of the late Kimmeridgian (Figure 6). From the *Elegans* zone to *Wheatleyensis* and up to the Fittoni zone, oxygen isotope curves point to progressive slighly more positive values in all basins, suggesting a climatic deterioration with colder sea water temperatures (Figure 6). Together with the long-term late Jurassic sea-level fall, colder sea water temperatures would have been progressively less favourable for marine organic matter phytoplanktonic production and preservation, finally leading to the termination of the ORB system and to the widespread late Jurassic enrichments in organic matter at the sea bottom in the NW European Basins. In addition, Zuo et al. [2019] evidenced "short term" fluctuations in humid/arid conditions during the Kimmeridgian using clay mineral associations, as shown in the North Aquitaine Platform in France [Colombié et al., 2018]. Such shorter-term climate fluctuations during the Kimmeridgian and the Tithonian, possibly associated with sea-level changes, may have modulated the NW European ORB record, as shown by the succession of several ORB through time and the cyclic pattern of the organic record.

6. Conclusions

Using newly described cores and outcrops, we characterised, thanks to Rock-Eval Pyrolysis and palynofacies observations, the organic matter content of marine platform deposits at the Oxfordian–Kimmeridgian transition in the Boulonnais area (NW France). Organic rich deposits in outer to inner platform environments occur in the uppermost *Cymodoce* to the late *Mutabilis* zone interval (early late Kimmeridgian), with TOC reaching up to 3.4 wt% and HI up to 402 mgHC/gTOC. Organic sources correspond to a mixture of a Type III (continental) and Type II (marine) organic matter, as shown by palynofacies. The organic-rich deposits were associated with enhanced planktonic palaeoproductivity and/or dysoxia/anoxia in water masses. In platform deposits of Normandy and Charentes in France, equivalent organic rich intervals can be evidenced at the Oxfordian–Kimmeridgian transition. Re-interpreting previously published data from Yorkshire and Dorset in the UK, again, similar organic-rich deposits also exist in the late *Cymodoce* and in *Mutabilis* zones in the UK, and can be considered as Organic Rich Bands (ORB), as described in NW Europe during the Late Jurassic. We thus propose that the ORB deposition system at the NW European scale, which lasted until the middle part of the Tithonian over a time span of 6.8 Myr, began earlier than previously thought, at the *Cymodoce–Mutabilis* boundary during the early late Kimmeridgian. This time-interval was also marked by a pronounced sea water warming as high as 6 °C, recorded in NW Europe by most authors. Sea water temperature remained rather stable but elevated during most of the Kimmeridgian and Early Tithonian, an interval corresponding to multiple well-known ORB deposits in NW European basins, followed by a cooling trend during the middle and upper part of the Tithonian, the latter corresponding to the end of the ORB deposition. We thus proposed that early late Kimmeridgian warmer climatic conditions played a role in enhancing palaeoproductivity and/or favouring organic matter preservation on the sea floor as a major trigger for Late Jurassic ORB deposits, together with the long-term sea level rise, the peculiar physiographic conditions in NW European basins, and probably modulated by shorter-term climatic changes.

Conflicts of interest

Authors have no conflict of interest to declare.

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Supplementary data

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