

Late Cenomanian-Turonian isotopic stratigraphy in the chalk of the Paris Basin (France): a reference section between the Tethyan and Boreal realms

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Abstract – A chemostratigraphic study ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of the Late Cenomanian and Turonian chalk succession from the “Craie 701” Poigny borehole (near Provins in the Paris Basin, France) provides new high-resolution stable carbon and oxygen isotope data. Correlation of the bentonite horizons and the isotopic trends from Poigny with its English Chalk equivalent allows the development of a precise stratigraphic framework. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ variations are synchronous and widespread throughout the European epicontinental seas and Tethyan Ocean. In the Poigny borehole, the Oceanic Anoxic Event 2 (OAE 2) is marked by a large and brief positive excursion of carbon isotopes (a carbon isotope excursions: CIE of 3‰ amplitude) without any apparent anoxia in the Late Cenomanian Chalk. Comparisons between different key sections on a North-South transect from the Anglo-Paris Basin to the Umbria-Marche Basin (Gubbio Section, Italy) and the Vocontian Basin (South-East France), suggests that the OAE 2 is linked to an increase in marine organic matter production, modulated by a regional effect on the organic carbon burial rate. Thus, the large positive carbon isotope increase spanning the Middle Cenomanian through to the Middle Turonian, including the salient CIE associated with the OAE 2, reflects a global scale increase in marine productivity that would be concomitant with a major long-term sea level rise. The stratigraphic position of the Turonian-Coniacian boundary can also be better defined by this isotopic study. A comparison of $\delta^{18}\text{O}$ data between the Anglo-Paris Basin and Tethyan Basin shows high-amplitude, long-term synchronous variations reflecting primary paleo-environmental changes which are independent of local facies, sediment thickness and diagenesis. In particular, a negative shift (–1‰ of amplitude) reflects a warmer climate regime, marking the onset of OAE 2. Two colder phases (+1‰ amplitude each) occurred in the Early Turonian and the beginning of the Late Turonian.

Keywords: Chemostratigraphy / Cretaceous / Cenomanian-Turonian / stable isotopes / Craie 701-Poigny borehole / Paris Basin

Résumé – **Stratigraphie isotopique de la craie du Bassin de Paris (France) du Cénomanién supérieur au Turonien: une série de référence entre les domaines téthysien et boréal.** Une étude chimiostratigraphique de la craie du forage de Poigny “Craie 701” (près de Provins, Bassin parisien, France) a permis d’acquérir de nouvelles données isotopiques (isotopes stables du carbone et de l’oxygène) à haute résolution sur l’intervalle Cénomanién à Coniacien basal. La comparaison en corrélant des niveaux de bentonites et les courbes du $\delta^{13}\text{C}$ et du $\delta^{18}\text{O}$ de Poigny avec celles de la série anglaise de Culver Cliff (Angleterre) de faciès sédimentaire identique donne un calage stratigraphique très précis des dépôts étudiés. Les variations isotopiques (carbone et oxygène) sont synchrones et généralisées dans toutes les mers épicontinentales européennes et dans l’océan Téthysien. L’événement anoxique océanique 2 (OAE 2) est marqué par une importante et brève excursion positive du rapport isotopique du carbone (CIE de 3‰ d’amplitude) dans la partie sommitale du Cénomanién du sondage Craie 701, dans un intervalle

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sédimentaire sans anoxie apparente. Un transect du bassin Anglo-Parisien jusqu'au bassin d'Ombrie-Marche (coupe de Gubbio, Italie), en traversant le bassin Vocontien, sud-est de la France, suggère que l'OAE 2 est lié à une augmentation de la production de matière organique marine modulée par un effet régional du taux d'enfouissement du carbone organique. Ainsi, la forte augmentation du rapport isotopique du carbone qui s'étend du Cénomaniens moyen au Turonien moyen, en englobant le CIE associé à l'OAE 2, refléterait une augmentation de la productivité marine à l'échelle mondiale. Celle-ci serait concomitante d'une hausse importante et à long terme du niveau marin. La position de la limite Turonien-Coniacien, qui était peu contrainte par les études biostratigraphiques, a pu aussi être mieux définie par cette nouvelle étude isotopique. Une comparaison de l'évolution des valeurs du $\delta^{18}\text{O}$ des séries sédimentaires des bassins Anglo-Parisien et Téthysien montre des variations synchrones de fortes amplitudes, indépendantes du faciès local, de l'épaisseur sédimentaire et de la diagenèse. En particulier, le passage à une configuration climatique plus chaude au début de l'OAE 2 est enregistré dans le Bassin parisien (pic de -1% d'amplitude), ainsi que deux événements plus froids ($+1\%$ amplitude chacun). Ils se seraient produits au Turonien basal et au début du Turonien terminal.

Mots clés : Chimiostatigraphie / Crétacé / Cénomaniens-Turonien / isotopes stables / Sondage Craie 701 de Poigny / Bassin Parisien

1 Introduction

Large paleo-climatic and paleo-oceanographic disturbances occurred during the Late Cretaceous. Most of these perturbations, such as oceanic anoxic events (OAEs; Schlanger and Jenkyns, 1976; Jenkyns, 2010), are recorded by the pronounced carbon isotope excursions (CIE) recognised in marine and terrestrial environments. The largest of these perturbations is the OAE 2, which took place at the Cenomanian-Turonian transition (*e.g.*, Tsikos *et al.*, 2004; Grosheny *et al.*, 2006; Erba *et al.*, 2013; Aguado *et al.*, 2016). This event is regionally expressed by particular facies that are rich in organic matter and have local names such as the “Black Band” in Yorkshire (England), the “Thomel level” in the Vocontian Basin (France) or the “Bonarelli level” in Umbria-Marche (Italy). In the Anglo-Paris Basin, the event is prominently expressed in the chalky succession by a dark-grey, marly interval called the “Plenus Marls”.

The associated pronounced positive CIE is synchronous throughout the Tethyan and Atlantic Oceans as well as in the epicontinental seas (Arthur *et al.*, 1988). The detail of the $\delta^{13}\text{C}$ profile of OAE 2 shows several distinct maxima (a, b, and c) which seem to be related to anoxic conditions in most oceanic sites (Voigt *et al.*, 2007; Joo and Sageman, 2014; Jarvis *et al.*, 2015). Other younger peaks, in the lowermost Turonian, are thought to be related to suboxic or oxic conditions (Takashima *et al.*, 2009).

The aim of this work is to highlight these paleo-oceanographic events in an epicontinental sea domain, in the central part of the Paris basin, which is in an intermediate position between the English chalk domain and the Tethyan realm (SE of France and central Italy). In 1999, two deep boreholes (Craie 701-Poigny, N 48°32'6"-E 3°17'33" and Craie-702-Sainte-Colombe, N 48°32'20"-E 3°15'25") were drilled in the chalk of the Paris Basin, near Provins (Hanot, 2000, Fig. 1). It is in this eastern part of the Paris Basin that the chalk deposits reached a maximum thickness of 700 m. Both holes recovered an apparently complete (and nearly 700 m thick succession) that extends from the Late Cenomanian to the Campanian, which could potentially be used for the correlation of biostratigraphic and geochemical events between the

Tethyan and Boreal realms (Mégnién and Hanot, 2000; Robaszynski *et al.*, 2005). In the Poigny borehole, we sampled a 270 m thick interval spanning the Cenomanian through to the Turonian-Coniacian boundary.

By generating a long-term carbon isotope profile from the Early Cenomanian to the Early Coniacian, we aimed to detect $\delta^{13}\text{C}$ events and to test their potential for intra- and interbasinal correlations. In order to place the Poigny $\delta^{13}\text{C}$ record at a large scale, we compared it with reference sections located along a North-South transect (Fig. 1), including the Culver Cliff section in England (Paul *et al.*, 1994; Jarvis *et al.*, 2001; Jarvis *et al.*, 2006) and Hyèges, Angles, Vergons and Lambrous sections of the Vocontian Basin (Mort *et al.*, 2007; Takashima *et al.*, 2009; Gyawali *et al.*, 2017; Danzelle *et al.*, 2018; Gale *et al.*, 2018). A comparison with the pelagic Tethyan realm (Gubbio section; Jenkyns *et al.*, 1994) is also proposed. Thus, such transects across the European epicontinental sea and the Tethyan Ocean provide a better global understanding of paleo-environmental changes for the Cenomanian and Turonian stages. Climatic changes during the studied interval are also discussed on the basis of the $\delta^{18}\text{O}$ record.

2 Geological setting

2.1 The chalk in the Paris Basin

Since the 19th century, chalk from the Anglo-Paris Basin has been the subject of hundreds of stratigraphic studies (Mortimore, 1983; Pomerol, 1983; Mortimore, 2011; and references therein).

The formation of the Paris Basin began at the end of the Permian and its Mesozoic evolution was largely influenced by global plate tectonic events (*e.g.* the opening of the Atlantic Ocean or closing of the Tethys Ocean) and eustatic variations (*e.g.*, Guillocheau *et al.*, 2000). The European chalk deposits correspond to the maximum of the second first-order eustatic cycle (Hallam, 1984, 1992; Haq *et al.*, 1987; Haq, 2014). However, throughout its history, the Paris Basin has remained an epicratonic sea bordered by the Variscan massifs: the London-Brabant Massif to the East, the Armorican Massif to the West, and the Massif Central to the South (Fig. 1).

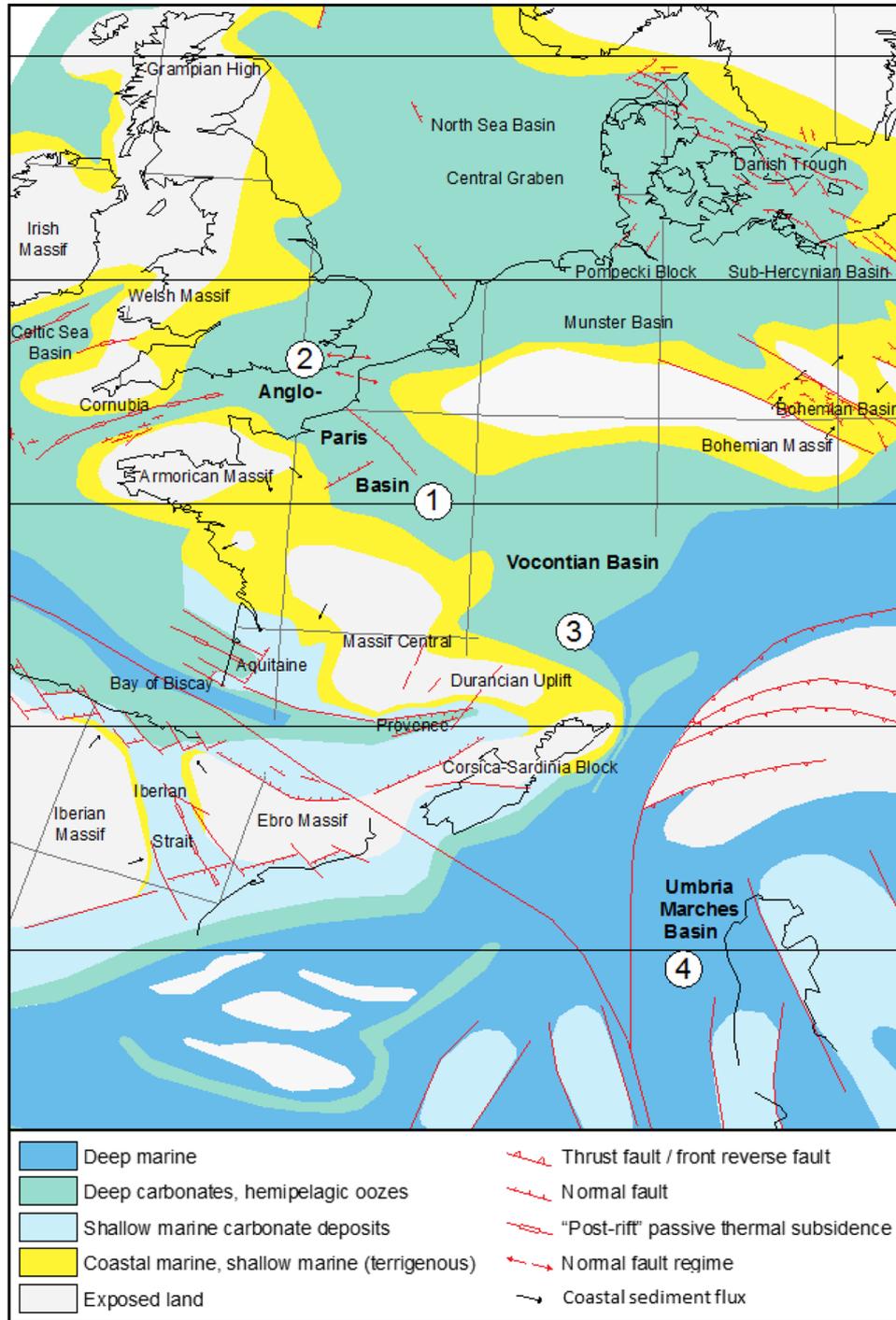


Fig. 1. Late Cenomanian paleogeography of Western Europe and a part of the Tethys (modified from Philip and Floquet, 2000). A rough location of some key sections: 1. Craie 701 borehole (this study); 2. Eastbourne, Sussex, UK (Paul *et al.*, 1994); 3. Lambruisse, Vocontian Basin, France (Takashima *et al.*, 2009); 4. Gubbio, Umbria-Marche Basin, Italy (Tsikos *et al.*, 2004).

After a major regression and the emergence of the basin at the end of the Jurassic, the first Lower Cretaceous deposits were essentially continental (Wealden facies), argillaceous and sandy due to the erosion of the surrounding continents. Marine conditions returned progressively from the East (during the Aptian) to the West (during the Albian). During the Late Cretaceous, very high sea levels allowed the invasion of this

epicontinental platform by pelagic organisms, such as coccolithophoridae, leading to the homogeneous chalk deposits. Sedimentation was driven by several transgressive-regressive third-order cycles (Robaszynski *et al.*, 1998; Lasseur, 2007; Amédéo and Robaszynski, 2014), and the highest sea level occurred near the Cenomanian-Turonian boundary (Haq, 2014). Tectonic episodes, related to the

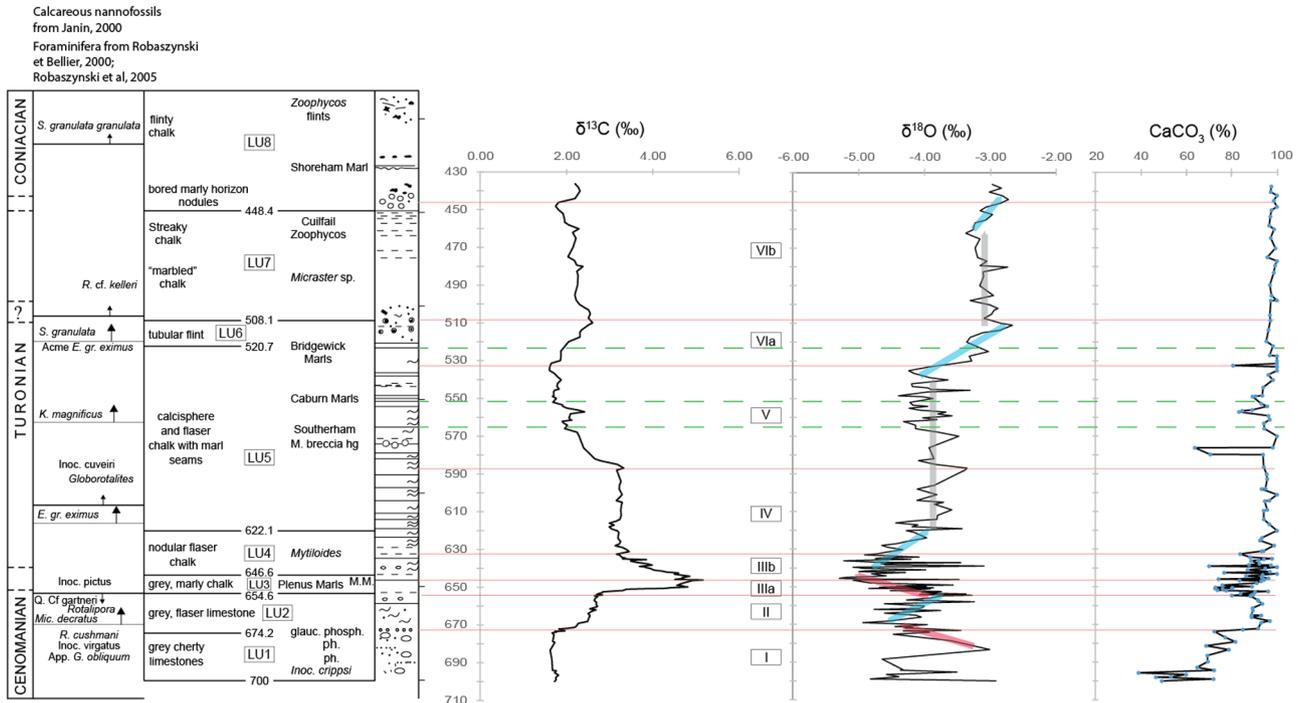


Fig. 2. Carbon and oxygen isotopic profiles of the Craie 701 borehole. Lithology (bentonite levels are identified by a green dashed line) and biostratigraphy are from [Robaszynski *et al.* \(2005\)](#). Subdivisions of the $\delta^{13}\text{C}$ profile into eight carbon isotope sequences (CIS) labelled I through VIII are also mentioned.

regional geodynamic evolution of the NW European basins, also had an influence on the depositional systems during the Middle Cenomanian to Lower Turonian and in the Upper Turonian intervals ([Deconinck *et al.*, 1991a](#); [Vandyckes and Bergerat, 1992](#); [Bergerat and Vandycke, 1994](#); [Lasseur, 2007](#); [Mortimore, 2011](#)). For example, more subsiding areas have been identified locally (Boulonnais, Aube) but, on the contrary, other areas show relative uplift and erosion (Pays de Caux, Normandy, Touraine).

The studied borehole ([Fig. 1](#)) is located in the centre of the Paris Basin between the North Bohemian Massif to the East and the whole range of the Armorican Massif (West) and Massif Central to the South, which is an area of several major oceanic circulations ([Voigt and Wiese, 2000](#)). Cooler water masses from the north may have flowed down along the Bohemian Massif; a north-westward shift of boreal currents is defined in the southern part of the basin and, also, in the North Atlantic water circulation along the England margin ([Voigt and Wiese, 2000](#)). The most subsiding part of the Paris Basin, during the Cenomanian and Turonian, is found near Provins (Seine-et-Marne), which was also a most open area to the pelagic Tethyan realm ([Lasseur, 2007](#)) between the north-west infra-tidal and the south-east bathyal domains throughout the Anglo-Paris Basin.

2.2 Lithology of the Craie 701-Poigny borehole

The two boreholes at Poigny and Sainte-Colombe were drilled as part of the Craie 700 programme, initiated by the Paris Basin Geologists Association and the French Compagnie Générale de Géophysique. These cores are stored at the core library of Rennes1 University (France). The initial objective of

this project was to understand the variations of the seismic wave velocity in the chalk which had remained unexplained after more than 50 years of petroleum exploration ([Hanot, 2000](#)). Despite the fact that the chalk turned out to be one of the hardest rocks to core due to rapid equipment breakage caused by flints, nodular chalks and fractures ([Mortimore, 2014](#)), recovery reached 98%. From an applied geology perspective, the main result was the occurrence of a 17 m thick, dolomitic unit, located at a depth of 168 to 185 m (from the surface) in the Craie 702-Sainte-Colombe hole ([Pomerol, 2000](#)), whereas the same stratigraphic interval drilled at Poigny (Craie 701 borehole, [Robaszynski, 2000](#); [Robaszynski *et al.*, 2005](#)) showed the usual chalk facies. Therefore, in order to prevent diagenetic artefacts, the Craie 701 borehole was chosen for the geochemical analysis.

The Craie 701 borehole displays an apparently continuous 650 m thick chalk succession from the Early Cenomanian to the Campanian-Maastrichtian boundary ([Robaszynski and Bellier, 2000](#)). The detailed lithology ([Fig. 2](#)) was described by [Barrier \(2000\)](#), [Robaszynski \(2000\)](#) and [Robaszynski *et al.* \(2005\)](#). Eleven lithological units (LU) have been described. The oldest eight were studied here. Briefly, the facies encountered in these LU are the following, from older to younger strata:

- **LU1** (700.00 to 674.20 m): hard grey cherty limestone with phosphatic and glauconite conglomeratic levels;
- **LU2** (674.20 to 654.60 m): grey flaser limestone composed of calcispheres cemented with calcite and partly with dolomite. A 40 cm thick conglomerate marks the base of this unit;
- **LU3** (654.60 to 646.60 m): grey marly chalk. This unit can correspond to the Anglo Paris Basin Plenus Marls

Formation (Jefferies, 1963), considering the highest occurrence of the benthic foraminifera *Rotalipora cushmani* at 651.80 m (Robaszynski *et al.*, 2005);

- LU4 (646.60 to 622.10 m): nodular flaser chalk;
 - LU5 (622.10 to 520.7 m): calcispheres and hard flaser chalk with frequent marl beds.
- The three marly layers, corresponding to bentonite levels, are described: the Bridgewick Marl (at 523 m), the Caburn Marl (at 550.5 m) and the Southerham Marl (at 566.70 m; Deconinck *et al.*, 2005; Robaszynski *et al.*, 2005; Lasseur, 2007; Mortimore, 2011);
- LU6 (520.70 to 508.10 m): chalk with tubular flints;
 - LU7 (508.10 to 448.40 m): “marbled” and grey chalk with large bioturbation structures and some flints at the base of this unit;
 - LU8 (448.40 to 427.60 m): white chalk with hard nodules.

The observed chalk succession is comparable to those described in the Boulonnais and the Aube areas, as well as in England, especially for the Cenomanian/Turonian transition where the eight characteristic levels of Plenus Marls were observed in the Aube (Amédro *et al.*, 1978; Amédro *et al.*, 1979; Robaszynski *et al.*, 1987; Amédro *et al.*, 1997; Amédro and Robaszynski, 2000; Amédro and Robaszynski, 2008).

2.3 Biostratigraphy of the Craie 701-Poigny Borehole

A chronostratigraphic framework of the Craie 701 borehole was established for the Cenomanian-Campanian succession based on planktonic and benthic foraminifera, calcareous nannofossils and dinoflagellates (Janin, 2000; Masure, 2000; Robaszynski and Bellier, 2000; Robaszynski *et al.*, 2000, 2005). Ammonites are relatively rare in this part of the basin. In contrast, inoceramids are abundant. Bioclasts are composed of echinoderms, inoceramids and siliceous sponges. Thus, each stage boundary is proposed on the basis of a set of biostratigraphic data and regional lithological markers recognised from outcrops in the Anglo-Paris Basin (Mortimore *et al.*, 2001; Mortimore, 2014 and references therein; Fig. 2).

The Cenomanian-Turonian boundary should occur in the 651.8–640.3 m interval (Figs. 2 and 3). This boundary is located, from lithological arguments, above the Plenus Marls equivalent (LU3) and near the base of the nodular chalk (646.6 m). From biostratigraphic data, it could be located between the LADs (Last Appearance Datums) of *R. cushmani* (651.80 m) and *Inoceramus pictus* and the FAD (First Appearance Datum) of *Mytiloides mytiloides* (643.00 m) (Robaszynski *et al.*, 2000, 2005). A Turonian age for the overlying sediments is confirmed by the first occurrences of *Globorotalites sp.* (609.9 m), *Stensioeina granulata* (526.6 m) and *Reussella cf. kelleri* (510.1 m).

The Turonian-Coniacian boundary is poorly constrained. Initial proposals ranged from approximately 530 m (Janin, 2000; taking the abundance of the nannofossil *Eiffellithus gr. eximius*) to 500 m (Robaszynski *et al.*, 2000), then to 450 m (Robaszynski *et al.*, 2005). Lasseur (2007) proposed to relocate this boundary to around 500 m. The lower and upper boundaries of the Turonian will be refined later (see section 5), on the basis of carbon isotope correlation.

3 Samples and methods

The Cenomanian-Turonian interval was sampled (198 samples) from 700 m (at the base of the core) to 436 m (middle of LU8), with a sampling interval ranging from 50 cm to 3 m, depending on the lithology and stratigraphic boundaries.

Bulk samples were crushed using an agate mortar. Calcium concentration measurements were performed using a Calci-meter. The CO₂ pressure generated by the reaction of hydrochloric acid (30%) and the powdered sample (100 mg) was converted to calcium carbonate content.

Carbon and oxygen stable isotopes were measured using a dual inlet system Delta V Advantage mass spectrometer, coupled with a Carbo-Kiel Device for automated CO₂ preparation from carbonate samples (30 to 40 µg). The reaction was produced by adding phosphoric acid to individual samples at 70 °C. Isotopic data are reported in conventional delta (δ) notation, relative to the Vienna Pee Dee Belemnite (VPDB). An internal standard has been calibrated to the NBS-19 reference standard. Analytical uncertainties based on replication and standard analyses are ±0.05‰ for carbon isotopes and ±0.08‰ for oxygen isotopes.

4 Results

4.1 Calcium carbonate content

A comparison of the evolution of the carbonate content (% CaCO₃) with respect to the LUs shows that LU1 corresponds to the lowest values (an average of 50 to 60%) with a gradual increase to 81% (Fig. 2). The boundary between LU1 and LU2 is marked by a sharp increase, up to 91%. The percentage of CaCO₃ values then remain relatively stable in LU2. In LU3 (which corresponds to the Plenus Marls Formation, latest Cenomanian), the carbonate content first decreases (down to 73%) in the lower part of the unit, and then increases (from 70 to 100% in its upper part, to the base of LU4).

In the remaining interval, *i.e.* LU4 through LU8, the CaCO₃ content remains high with a slight, long-term evolution from an average of about 92% (from the top of LU4 to LU5) to an average of 98–100% (within LU7 and LU8). This long-term increase is interrupted by three significant decreases: down to 63% at 576.2 m, just below a breccia hardground, 83% at 556.5 m, which coincides with pyritic chalk, and 80% at 532.5 m. This interval corresponds to a lower overall trend of values (down to 90%) in the upper part of LU5.

4.2 Bulk carbon isotopes

The evolution of the carbon isotope ratio (δ¹³C) shows high-amplitude fluctuations (from 1.6 to 5.2‰) that we used to define eight isotopic sequences, labelled CIS (Carbon Isotope Sequence) I to VI (Fig. 2).

In CIS I, δ¹³C values are low and very stable (1.7‰). This sequence corresponds to LU1. In CIS II, an increase of ~1‰ is observed until an interval of relatively stable values (2.7‰) formed a plateau matching LU2.

CIS III corresponds to the Cenomanian-Turonian boundary interval, with a positive δ¹³C excursion (CIE) reaching 5.17‰, which documents the OAE 2. This interval is studied in detail

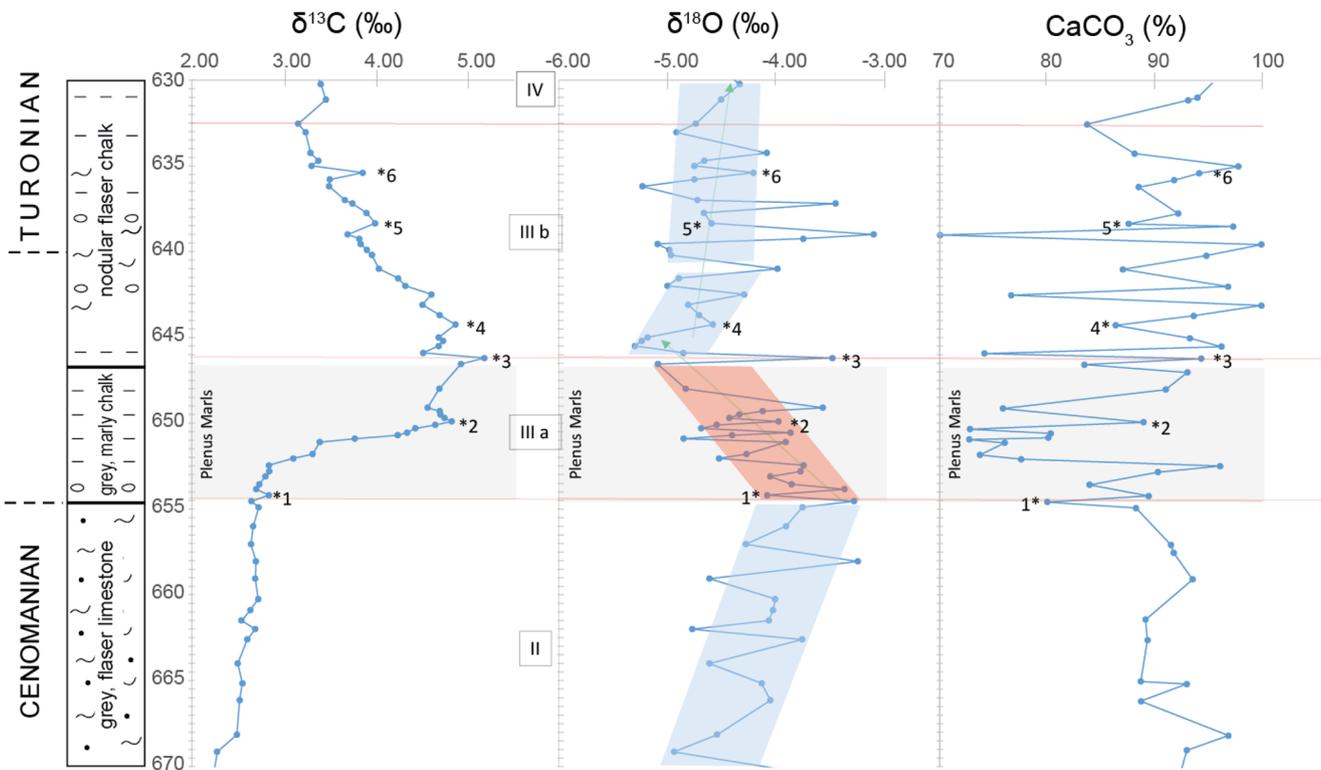


Fig. 3. Carbon and oxygen isotopes and carbonate content data of the Craie 701 borehole across the Cenomanian-Turonian boundary.

by Boulila *et al.* (2020). Based on cyclostratigraphic interpretation, these authors have shown an exceptionally well-defined carbon isotopic event with distinct onset and end. We propose to divide this into two sub-intervals: CIS IIIa, corresponding to the increasing part of the CIE, and CIS IIIb to its decreasing part (down to 3.3‰). CIS IIIa corresponds to the main part of LU3 (Plenus Marls, Fig. 3) and CIS IIIb to the lower part of LU4. In detail (Fig. 3), the increase in CIS IIIa shows three peaks, labelled 1 to 3, and the decrease in CIS IIIb has three minor peaks, labelled 4 to 6.

CIS IV (Fig. 2), which shows a plateau of relatively high values (3.3‰), corresponds to the uppermost part of LU4 and the lower part of LU5. After this plateau, a progressive decrease down to 1.6‰ characterises the CIS V isotopic sequence ending at 536 m and corresponding to the middle part of LU5. This decrease is interrupted by two positive peaks: the first at 2.42‰ (557.15 m) and the second at 1.88‰ (540.15 m).

A small, positive excursion between 536 and 450 m (culminating at 510 m, 2.6‰) defines CIS Va and b. These isotopic sequences correspond to the uppermost part of lithological sequence LU5 and sequences LU6 and LU7. The end of this excursion coincides with a low $\delta^{13}\text{C}$ value of 1.82‰ (450.2 m), which matches the LU7-LU8 boundary.

4.3 Oxygen isotopes

In the Upper Cenomanian and basal Turonian sediments (CIS I to CIS III, Fig. 2), oxygen isotopic ratio ($\delta^{18}\text{O}$) is very unstable with the amplitude of variations ranging from -3.1‰ to -5.2‰ . In the rest of the Turonian (up to 628 m, sequences

CIS IV to VI), the values are more stable, and the $\delta^{18}\text{O}$ variability becomes lower than 1‰. Two important and regular value plateaus could be distinguished. In the first, $\delta^{18}\text{O}$ is around -4‰ (CIS IV and V), and in the second it is approximately -3‰ (CIS VI), with a steep transition between these two plateaus (from 535 to 515 m).

Despite the high $\delta^{18}\text{O}$ variability in the base of the core, several detailed trends can be observed in the Cenomanian and Cenomanian-Turonian boundary intervals (Figs. 2 and 3). In the basal sequence LU1-CIS I, it is impossible to distinguish a clear evolution in the mean $\delta^{18}\text{O}$ values. Trends become more evident from CIS II, where the mean $\delta^{18}\text{O}$ values increase from approximately -4.8‰ to -3.2‰ (Fig. 2). The following sequence (LU3-CIS IIIa, Plenus Marls) shows a significant decrease down to -5.2‰ , and are the lowest values observed for the whole of the studied succession. It should be noted that these negative values are synchronous with the positive excursion of $\delta^{13}\text{C}$ (Figs. 2 and 3). A positive excursion occurs in the sequence CIS IIIb: values rise to -3.2‰ then decrease to around -4.8‰ near the boundary between CIS IIIb and CIS IV. At the base of CIS IV, the $\delta^{18}\text{O}$ values gradually increase to reach 610 m, at the plateau of about -4‰ described above.

5 Discussion

5.1 Stratigraphy of the chalk succession in the Craie 701-Poigny Borehole

To analyse the sequence of Late Cenomanian and Turonian paleo-environmental changes and to test their global or regional characteristics, it is necessary to have a very precise

stratigraphic framework. Due to the scarcity of biostratigraphic markers in the Paris Basin chalk, global stratigraphic correlations with Boreal and Tethyan realms are complex. Carbon isotope chemostratigraphy is a powerful tool to establish a correlation framework for the Cenomanian and Coniacian deposits (Accarie *et al.*, 1996; Voigt and Hilbrecht, 1997; Stoll and Schrag, 2000; Amédéo *et al.*, 2005; Voigt *et al.*, 2007; Joo and Sageman, 2014; Jarvis *et al.*, 2015). $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{13}\text{C}_{\text{org}}$ profiles during this time interval are similar for several marine and non-marine sections, implying a global response of the carbon cycle (Accarie *et al.*, 1996; Amédéo *et al.*, 2005; Joo and Sageman, 2014; Jarvis *et al.*, 2015).

Therefore, we refined the chronostratigraphy of the Craie 701 borehole by using bentonite levels, which have been defined as isochronous and recognised throughout the basin from England to Germany (Deconinck *et al.*, 1991b; Wray, 1999; Vanderaveroet *et al.*, 2000; Godet *et al.*, 2003; Robaszynski *et al.*, 2005). We compared the isotopic and biostratigraphic data with those of a stratigraphically well-constrained reference section with similar lithological deposits: the Culver Cliff section on the Isle of Wight (Scholle and Arthur, 1980; Paul *et al.*, 1994; Jarvis *et al.*, 2001; Mortimore *et al.*, 2001). This section was chosen because the observed lithological succession completely covers the studied interval and contains five bentonite levels in the Turonian. In the following, we used the biostratigraphic, isotopic and radiochronological synthesis of this section, provided by Jarvis *et al.* (2006).

The $\delta^{13}\text{C}$ fluctuations are very similar between the Culver Cliff section and the Craie 701 borehole, both in form and in absolute values (Fig. 4). At the base of the Craie 701 borehole, CIS I corresponds to the lower values observed in the Early Cenomanian in England. The first significant increase in $\delta^{13}\text{C}$ (about +0.7‰ at 675.2 m) can be correlated with the mid-Cenomanian Event 1. The occurrence of *Inoceramus crippsi* and *Inoceramus virgatus* in the core supports this correlation (Figs. 2 and 4). Since the small peak observed at 694 m may correspond to the one at Culver Cliff at 5 m, the Albian-Cenomanian boundary should be close to the base of the core. In Italy, the Contessa Quarry section also exhibits a large positive excursion of 1‰ during the Cenomanian (Stoll and Schrag, 2000).

The $\delta^{13}\text{C}$ plateau corresponding to CIS II is also present in the Culver Cliff curve, but its extent is greater (55 m). It corresponds to the Middle and Upper Cenomanian intervals. In detail, the end of the observed increase at 662 m and the beginning of the first plateau can be correlated with the Jukes Browne event defined in England. The first occurrence of *Rotalipora* spp. at 675 m allows us to confirm the Cenomanian age of these deposits.

The huge positive excursion (CIS IIIa and b), corresponding to the well-known OAE 2, is similar in both sections. It encompasses with the Plenus Marls and the Cenomanian-Turonian transition. This is consistent with the last occurrence of *R. cushmani*, observed between 651 and 652 m (Robaszynski and Bellier, 2000; Robaszynski *et al.*, 2005). In detail, peaks 2 and 3 occur during the increase of $\delta^{13}\text{C}$ (Fig. 3) and are located in the end part of and just above the Plenus Marls, respectively. They coincide with peaks a and b of the same formation, defined by Jarvis *et al.* (2006), at Culver Cliff (Fig. 4). The “trough interval” between these peaks is also observed in both sections.

The Cenomanian-Turonian boundary is positioned in England and in the Paris Basin (Boulonnais, Pays de Caux, Aube) above the Plenus Marls (in the Mead Marls) at the level of the first minor peak observed during the progressive decrease of the $\delta^{13}\text{C}$ (peak c). This peak seems to correspond to the minor isotopic event labelled 4 in the Craie 701 borehole. If correct, the stage boundary would be at 644 m, *i.e.* 2.6 m above the lithological boundary (646.6 m). This coincides with the interval proposed by the biostratigraphic data: between the last occurrences of *R. cushmani* and of *I. pictus* (651.8 m) and the first occurrence of *M. mytiloides* (643 m), *cf. supra*. More recently, the boundary has been precisely replaced on the basis of a fine cyclostratigraphic correlation between records from Poigny and Eastbourne, together with additional calcareous nannofossil data from Poigny (Boullila *et al.*, 2020). In the final part of the Cenomanian-Turonian $\delta^{13}\text{C}$ excursion, minor peak 5 (638 m) should correspond to the Holywell event, defined at Culver Cliff. The same observations are made by Voigt *et al.* (2007) in Germany. An identical correlation between the isotopic signal and the CaCO_3 trend is also observed, *i.e.* relatively high values for isotopic peak 1 and a drop for peaks 2 and 3.

The second isotopic plateau (IV) has its equivalent in England, in the Early Turonian and the lower part of the Middle Turonian (Fig. 4). In detail, the Lulworth and Round Down events can be recognised in the Craie 701 borehole at 618 m and 594 m, respectively. These correlations are consistent with the presence of *Inoceramus cuvieri* and the appearance of *Globorotalites* and *E. gr.eximus* (Robaszynski and Bellier, 2000; Robaszynski *et al.*, 2005).

After this plateau, the progressive decrease in the $\delta^{13}\text{C}$, down to the lowest values, is similar in both sections but the isotopic correlations are not so evident. Nevertheless, specific lithological levels may support the proposed isotopic correlation. The breccia located at 574 m in the Craie 701 borehole can be correlated with the Ogbourne Hardground. Voigt *et al.* (2007) also recorded this isotopic decrease, which also coincides with a significant decrease in carbonate contents in the studied core (Fig. 2). Three other clay horizons, corresponding to bentonites (Deconinck *et al.*, 2005; Robaszynski *et al.*, 2005), located in the core at 566.7 m, 550.5 m and 523 m can be well correlated with those described in the Upper Turonian of Culver Cliff, respectively, as Southerham Marl (B2), Caburn Marl (B3) and Bridgewick Marl (B4). The upper part of the LU5 may be dated to the beginning of the Late Turonian. The isotopic increase observed at 510 m in the studied succession may be correlated with the Hitch Wood event from the Culver Cliff trend and the following decrease (up to the Navigation event) with the LU7-LU8 lithological boundary at 449 m. A similar increase is also observed in Italy (Stoll and Schrag, 2000). The Turonian-Coniacian boundary coincides with these low values and should be located in the Craie 701 borehole at approximately 448.5 m. This is also consistent with the position of the Shoreham Marl bentonite level (B6 at Culver Cliff), at 424.9 m in the Craie 701 succession (Robaszynski *et al.*, 2005).

The absolute isotopic values from the Turonian deposits are consistent in both sections. This boundary location is close to that proposed (444 m) by Robaszynski *et al.* (2005). The biostratigraphic framework of Janin (2000), which locates the boundary at 530 m, and that of Lasseur (2007), at 500 m, cannot be retained in this case.

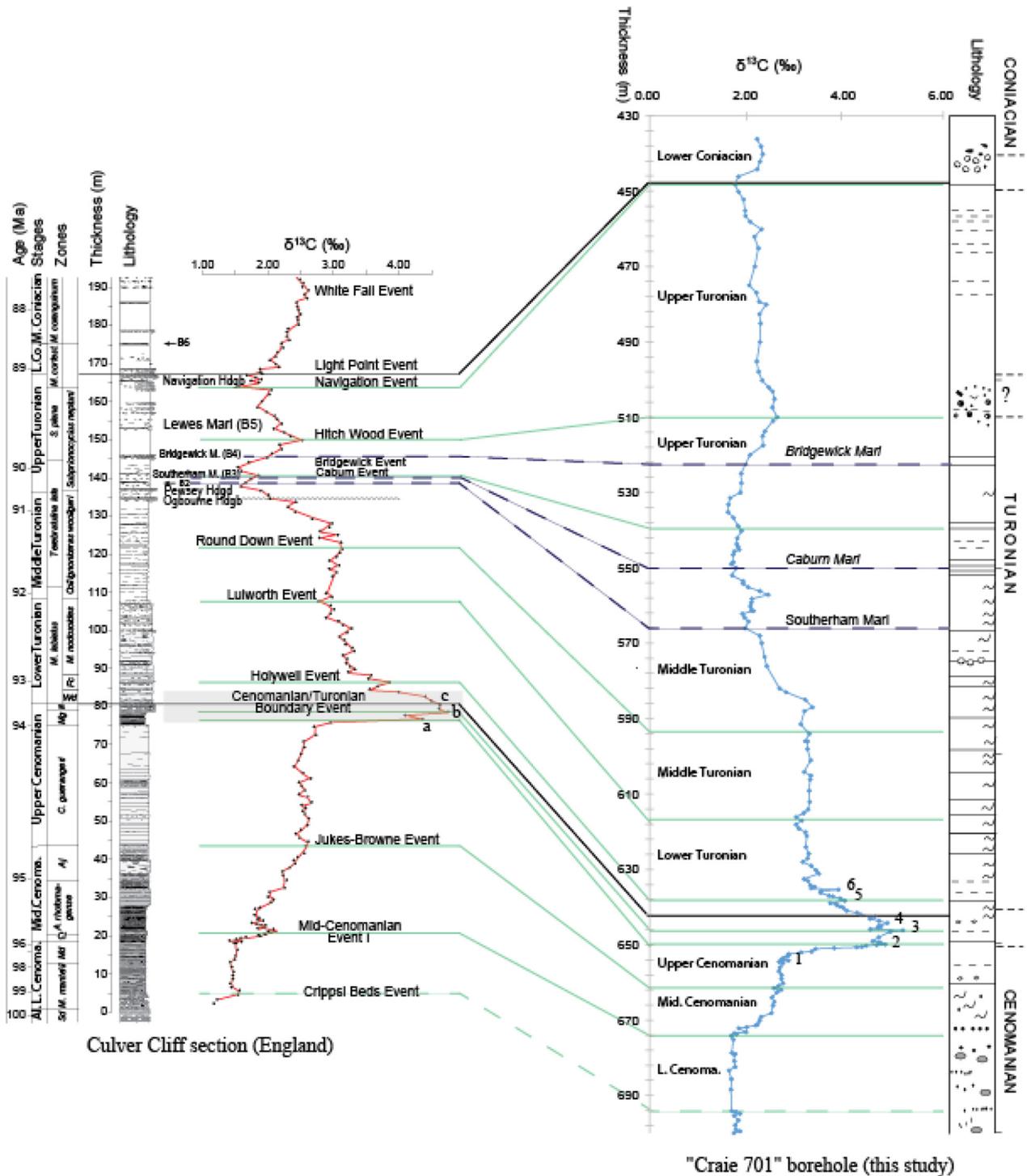


Fig. 4. Correlation of the Culver Cliff section (Paul *et al.*, 1994; Jarvis *et al.*, 2001, 2006) with Craie 701 borehole Cenomanian-Turonian $\delta^{13}\text{C}$ curves. Abbreviations: Alb–Albian; Ce–Cenomanian; *Sd*–*Stoliczkaia dispar*; *Mm*–*Mantelliceras mantelli*; *Md*–*Mantelliceras dixonii*; *Ci*–*Cunningtoniceras inerme*; *Ar*–*Acanthoceras rhotomagense*; *Aj*–*A. jukesbrownei*; *C*–*Calycoceras guerangeri*; *Mg*–*Metoicoceras geslinianum*; *N*–*Neocardioceras juddii*; *Wd*–*Watinoceras devonense*; *Fc*–*Fagesia catinus*; *Mn*–*Mammites nodosoides*.

A comparison of the sedimentation thickness in both sections shows differences in the Cenomanian (50 m in the Craie 701 borehole *versus* 75 m in the Culver Cliff section) and in the Lower and Middle Turonian (70 m *versus* 55 m). In contrast, the thickness of the Upper Turonian deposits is very

different between the two sites: about 120 m in the Craie 701 borehole and only 30 m in England. Sedimentation rate estimates, based on bentonite horizon correlations, have shown an important dilatation (up to three times greater) for the Turonian deposits from the Aube compared to the Boulonnais

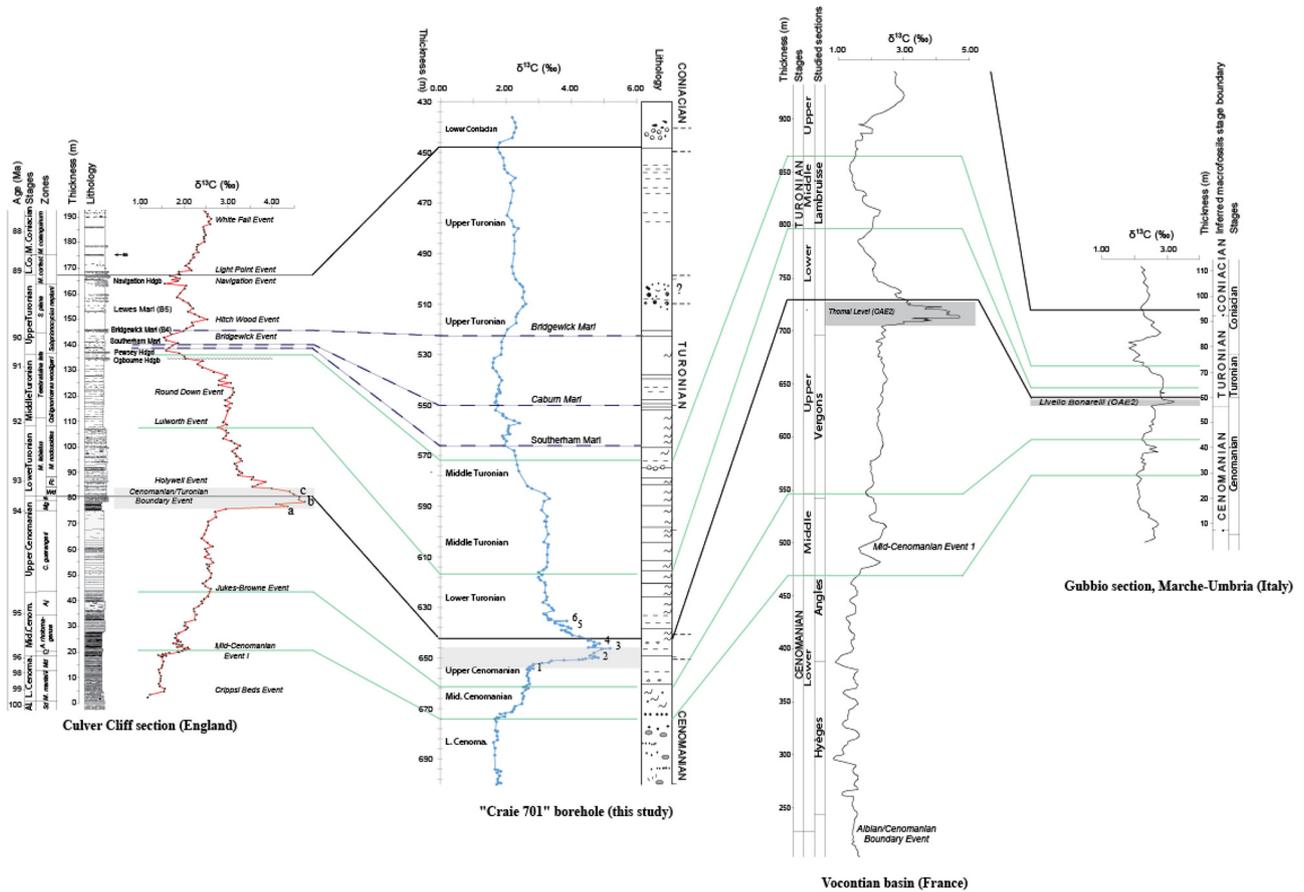


Fig. 5. Correlation of Culver Cliff section (Paul *et al.*, 1994; Jarvis *et al.*, 2001, 2006), Craie 701 borehole, Vocontian Basin sections (Takashima *et al.*, 2009; Gyawali *et al.*, 2017) and Gubbio succession (Jenkyns *et al.*, 1994) Cenomanian-Turonian $\delta^{13}\text{C}$ curves.

Series, which is seemingly an area with less subsidence (Vanderaveroet *et al.*, 2000). The German chalk succession also shows a thicker series than the English one (Wray, 1999). The reduced thickness of the Culver cliff section can be explained by the occurrence of several hardgrounds within this interval, from the Ogbourne to the Navigation hardgrounds. A new episode of tectonic instability during the Upper Turonian controlled subsiding zones along a major NW-SE trending axis (Aube) and uplifted areas in England and Normandy (Deconinck *et al.*, 1991a, b; Vandyckes and Bergerat, 1992; Bergerat and Vandycke, 1994; Mortimore *et al.*, 1996; Mortimore and Pomerol, 1997; Lasseur, 2007).

5.2 Carbon isotopic ratio evolution from epicontinental seas to pelagic realm during the Cenomanian-Turonian

After correlating the $\delta^{13}\text{C}$ evolution curve for the epicontinental domain of the South-East Paris Basin with that of southern England, we can extend this approach to the Tethyan pelagic domain with the Vocontian Basin (Hyèges, Angles, Vergons and Lambruisse sections) using the data of Gyawali *et al.* (2017) and Takashima *et al.* (2009) and the Umbria-Marche Basin (Italy, Gubbio section) using the data of Jenkyns *et al.* (1994).

First of all, we must note the similarity of the general shape of the $\delta^{13}\text{C}$ evolution curves at the four sites (Fig. 5). However, the equivalent thickness of the various isotopic events is variable from one basin to another due to very different sedimentation rates between sites (epicontinental and pelagic realm). So, the thickness of the studied interval is about 165 m in the south of England, 250 m in the Craie 701 borehole, about 700 m in the Vocontian Basin and 85 m in Umbria-Marche. In detail, if we examine the major positive excursion around the Cenomanian-Turonian boundary at each location, we observe that its thickness is 8 m in England, 20 m in the southeast Paris Basin, 40 m in the Vocontian Basin and 3 m in Umbria-Marche. Minor isotopic events in the condensed pelagic Italian section may be difficult to discern compared to the epicontinental sections or the hemipelagic basin.

Concerning the absolute values of $\delta^{13}\text{C}$, Figure 6 compares the isotopic ratios of the selected sections. We observe that during the Early Cenomanian, the $\delta^{13}\text{C}$ values are relatively close at the four sites, around 1.5‰ in average in England and the Paris Basin. The lowest values with high variability correspond to the Vocontian Basin (from 0.8 to 1.7‰) and the strongest to Umbria-Marche (2.2‰). The carbon isotopic ratio then increases to reach the plateau preceding the major excursion of OAE 2. This plateau is present in the four curves and culminates around 2.6‰ but ranges from 2.1‰ (Vocontian) to 2.7‰ (the Craie 701 borehole).

The OAE 2 isotopic excursion is well marked at all sites however, its amplitude is variable. Two sites (south-east Paris Basin, Culver Cliff) have very strong amplitudes with a maximum of 4.8 and 5.2‰ respectively, while the excursion is less pronounced in Umbria Marche (maximum 3.2‰). So, we can see that the amplitude of the $\delta^{13}\text{C}$ excursion is greater in the shelf seas than in the open ocean. The ratio is generally higher in the Vocontian Basin (4.7‰), than in the Umbria-Marche Basin (3.2‰), although the latter is considered to be more open.

Such an observation was already made by Kaiho *et al.* (2014) in a platform-basin transect in Spain and southeastern France (Grosheny *et al.*, 2017). Deeper, more restricted basins are more favourable to anoxic conditions than shallower water realms. Ocean margin flooding could enhance the primary productivity which preferentially removed ^{12}C , causing waters to become enriched in the heavier isotope and therefore higher in $\delta^{13}\text{C}$ carbonates. The consequence in the deep part of the basin was the development of the oxygen minimum zone with more ^{12}C -enriched buried organic carbon.

Generally, the $\delta^{13}\text{C}$ carbonate depth transect from platform to basin shows lower values in the shallow-water sections and a higher ratio in the deep-water sections (Renard *et al.*, 1982; Patterson and Walter, 1994; Jenkyns, 1995; Weissert *et al.*, 2008; Schiffbauer *et al.*, 2017). This is also observed for the Cenomanian and Upper Turonian in the present work (Fig. 6). This may reflect stronger, land-derived organic component inputs, remineralisation of marine and terrestrial organic carbon, different carbonate factory (aragonite or calcite and high-Mg-calcite), or fluctuating sea level leading to subaerial exposure of shallow water sediments and diagenetic overprinting.

Several studies have shown that greater amplitudes in $\delta^{13}\text{C}$ are often recorded in shallow-water carbonate deposits than those seen in pelagic sections (Jenkyns, 1995; Vahrenkamp, 1996; Wissler *et al.*, 2003; Millan *et al.*, 2009; Weissert, 2018). In shallow-water settings, the isotopic composition of water, and, therefore, of carbonate sediment are less stable than in open seas. This could be due to numerous factors, such as marine productivity, nutrient input, temperature, atmospheric pCO_2 , etc.

The location of the $\delta^{13}\text{C}$ excursion, relative to the sedimentological expression of OAE 2, also seems to be somewhat different. Its maximum occurs inside the Thomel level in the Vocontian Basin (Takashima *et al.*, 2009), in the top part of the Plenus Marls in England (Jarvis *et al.*, 2006) and immediately above this level in the south-east Paris Basin. For Umbria-Marche, isotope analyses of bulk carbonates (Fig. 5; Jenkyns *et al.*, 1994) might suggest that the isotopic maximum occurs above the Bonarelli level. In fact, this pattern is an artefact due to the lithology of this level which is made of silica and organic matter and is completely free of carbonates (no isotopic analysis on such a mineralogy type is possible). Considering the isotopic curve for organic matter (Tsikos *et al.*, 2004; Mort *et al.*, 2007), the maximum $\delta^{13}\text{C}$ lies within the Bonarelli level. In summary, relative to lithology, the OAE 2 isotopic excursion is expressed earlier (within the level rich in organic matter) in the oceanic facies than in the epicontinental facies (at the top of the organic level).

In the Early and Middle Turonian, the post-excursion plateau (around 3‰) is observed in England, in the Paris Basin

and in the Umbria-Marche trends. This plateau is much less marked in the curve corresponding to the Vocontian Basin, where a large progressive decrease is observed (1.5‰). After this plateau, in the Late Turonian, the values drop in all sections to a minimum that is close to that of the Early Cenomanian. The curves then show a similar trend with a progressive excursion (around 2.5‰) leading to low values of $\delta^{13}\text{C}$ (of around 2‰) at the Turonian-Coniacian boundary.

There is no relationship between the paleo-latitude position of the sites and the isotopic fluctuations and absolute isotopic values (Fig. 5), suggesting that the environmental parameters are the most significant control of carbonate $\delta^{13}\text{C}$, compared to the climate.

5.3 Cenomanian-Turonian carbon isotope ratio: a proxy of the global carbon cycle modulated by the local environment

Globally, all isotopic fluctuations, from the Early Cenomanian to the Turonian-Coniacian boundary, are present in all marine settings. The main parameters controlling the fluctuations in the carbon isotopic ratio in the open ocean are marine productivity (organic and carbonate) and the preservation of organic carbon in sediments, in relation to the oxygen content of the seawater. On the marine platform, isotopically light, terrestrial organic matter may also influence the bulk signal of the sediments.

To distinguish the respective part of each of these parameters, it should be noted that the $\delta^{13}\text{C}$ increase of the Cenomanian-Turonian transition develops over quite a long period of time (from Middle Cenomanian to Middle Turonian). The evolution curve of $\delta^{13}\text{C}$ can be de-convolved into two events (Fig. 7). First, there is a large maximum corresponding to an increase of about 1 to 1.5‰ of the isotopic values, which covers the time interval between the Middle Cenomanian and Middle Turonian. This maximum is almost identical at all of the sites. Superimposed on this maximum is a sharp excursion just before the Cenomanian-Turonian boundary whose amplitude varies according to the sites (barely 1‰ in open pelagic areas, up to 2.5‰ in epicontinental areas).

The facies evolution in the Craie 701 borehole is consistent with this scheme. During the Early Cenomanian, low $\delta^{13}\text{C}$ values correspond to chalk with phosphatic pebbles, glauconite and a high content of quartz and bioclasts which may reflect oligotrophic oceanic water and lower organic and carbonate productivity (weak CaCO_3 ; Fig. 2). The increase in the isotopic carbon ratio at the beginning of the maximum (Middle Cenomanian) coincides with an increase in the calcium carbonate content in sediments and lower detrital inputs. Chalk is enriched in calcispheres, such as *Pithonella*, nannoconus (Amédéo *et al.*, 1978; Hart, 1991; Wendler *et al.*, 2010). This association characterises a high level CaCO_3 marine environment with oxygenated water and low terrestrial inputs. In numerous sections, the isotopic long-term maximum begins with a peak (called the mid-Cenomanian event 1) that is contemporary with an increase in the planktonic assemblages in sediments (Paul *et al.*, 1994; Robaszynski *et al.*, 1998; Jarvis *et al.*, 2006).

In the Early Turonian, the last part of the isotopic plateau may also correspond to organic and carbonate productivities

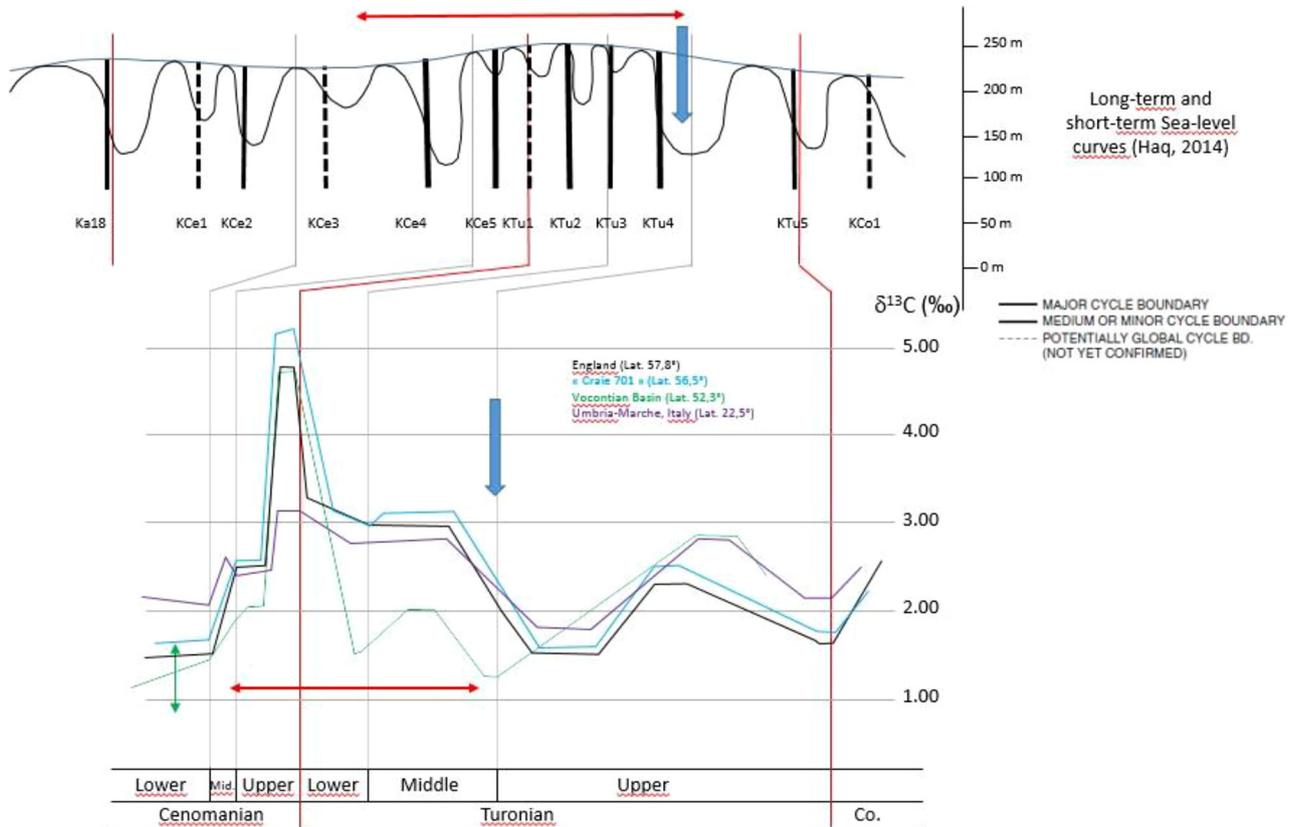


Fig. 6. Composite $\delta^{13}\text{C}$ curves for epicontinental basin (Culver Cliff section and Craie 701 borehole) compared with pelagic basin (Vocontian Basin sections and Gubbio succession) for the Cenomanian-Turonian interval. Comparison of the $\delta^{13}\text{C}$ curves with the sea level changes (Haq, 2014). The red line represents a high sea level time and the blue arrow a huge regression.

(Fig. 7). Abundant and diversified bioturbations have been recognised in the chalk just above the Plenus Marls, reflecting well-oxygenated water. The benthic diversity recovers rapidly in the higher beds of the Plenus Marls which coincide with lower siliciclastic content and the onset of the chalk deposits. High organic productivity in the beginning of the Turonian is confirmed by the abundance of pithonellids in the white chalk (Caus *et al.*, 1997; Wendler and Willems, 2002; Wendler *et al.*, 2002; Wilmsen, 2003; Wendler *et al.*, 2010). High siliceous productivity indices were also recorded in the Umbria-Marche Basin, by the radiolarian-rich Bonarelli Level (Danelian *et al.*, 2007; Musavu-Moussavou *et al.*, 2007). Thus, for the various marine environments, the facies corresponding to the isotopic maximum, show indices of high productivity but no sign of oxygen deficiency in the water. During the maximum sea-level, increased mobilisation of nutrients through transgressive erosion have contributed to subsequently high marine productivity.

Therefore, we postulate (Fig. 7) that the Middle Cenomanian to Middle Turonian maximum should be part of a global marine productivity increase event of almost identical magnitude in the European and Tethyan domains. The positive excursion of the Cenomanian-Turonian boundary would correspond to an acme of productivity increase, reinforced by better preservation of organic carbon in relation to oxygen depletion of the seawater that varies according to the regions and the environmental context (epicontinental seas *versus* open ocean).

During OAE 2, most of the sites also show a low calcium carbonate content when the carbon isotopic ratio is high (Tsikos *et al.*, 2004 and this study Figs. 3 and 7). An increase in volcanic emissions (from seafloor spreading and submarine intraplate volcanism) coincides with the OAE 2 event (Pitman, 1978; Schlanger *et al.*, 1981; Larson, 1991). Reduced deep ocean ventilation has also been proposed by Monteiro *et al.* (2012). This sluggish oceanic circulation within the Atlantic should be responsible for a breakdown in the vertical structure of the oceanic water column and restricted deep-water exchange (Erbacher *et al.*, 2001; Lüning *et al.*, 2004; Voigt *et al.*, 2004; Watkins *et al.*, 2005; Forster *et al.*, 2007; Tsandev and Slomp, 2009; Friedrich *et al.*, 2012; Monteiro *et al.*, 2012; Wagner *et al.*, 2013; Goldberg *et al.*, 2016). Enhanced CO_2 emission in the atmosphere may also be responsible for an increase in the acidity of ocean surface waters and, thus, the partial dissolution of carbonate particles (Boulila *et al.*, 2019).

The global evolution of the isotopic curve shows similarities with those of sea level fluctuations (Fig. 6) at the 3rd/2nd order scale (Haq *et al.*, 1987; Haq, 2014). Notably, the first and the final parts of the isotopic maximum correspond to the two high sea level stands of Cenomanian and Turonian age. These transgressive phases have allowed the observation of a mixed Boreal and Tethyan fauna in the chalk series of the Aube, but also allowed North American fauna to be present as far as Tunisia (Amédéo and Robaszynski, 2008).

This suggests that the productivities are induced by high sea levels. The important fast regression occurring at the

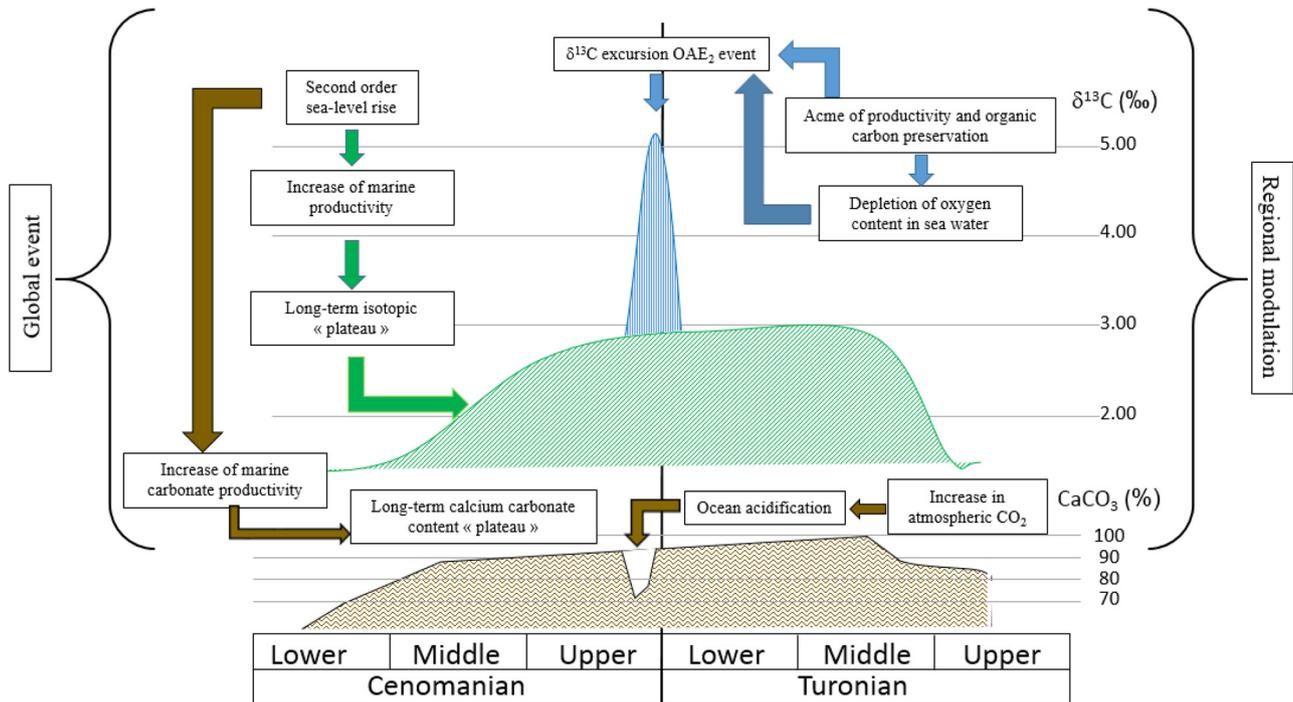


Fig. 7. Schematic trends and controls of the carbon isotopic ratio and calcium carbonate content of sediments across the Cenomanian-Turonian transition.

Middle-Late Cenomanian boundary coincides with an interruption (the Jukes Browne event) in the gradual increase up to the maximum of high carbon isotopic values. A 40 cm thick conglomerate is observed in the studied core at this level. The sharp $\delta^{13}\text{C}$ excursion of OAE 2 seems to be linked to a “minor” third order scale regression. This is also an argument for considering that another parameter added to productivity to drive this event. The low values observed in the Late Turonian would correspond to low sea levels (3rd scale) and the increase to the important transgressive phase at the Turonian-Coniacian boundary.

The sediments from the epicontinental sea (Anglo-Paris Basin) show higher carbonate and organic productivity from Late Cenomanian to Middle Turonian, which is recorded in the deposits through high $\delta^{13}\text{C}$ values (Figs. 5 and 6). High detrital nutrient input from the emergent area, under a warm and humid climate (Arthur *et al.*, 1988; Sarmiento *et al.*, 1988; Jenkyns, 1999; Handoh and Lenton, 2003; Voigt *et al.*, 2004; Forster *et al.*, 2007; Jenkyns, 2010; Föllmi, 2012; Aguado *et al.*, 2016; Nuñez-Useche *et al.*, 2016), may induce high marine productivity. Considering the long-term sea level rise and the associated increase in the epicontinental sea surface, the carbonate deposition rate should be more elevated in this realm. A similar pattern has already been observed in Tunisia (Accarie *et al.*, 1996; Amédéo *et al.*, 2005).

In Italy, the highest isotopic values in the Early Cenomanian and Late Turonian are explained by more stable trophic water conditions for the entire studied period. In the Anglo-Paris Basin at that time, low sea level and high terrigenous input from the continents disturbed the oceanic environment. More open conditions in the surface water and oligotrophic surface water may explain why, in the Early and

Middle Turonian, Italian deposits show a similar but lower trend compared to the epicontinental sea.

The first important sedimentological events in the Turonian (breccia and marl deposits in the Middle Turonian) coincide with a huge decrease in sea level at the third order scale. This trend is subsequently confirmed by the numerous hardgrounds observed in the Upper Turonian (Amédéo *et al.*, 1997). Ammonite and echinoid migrations indicate a shift in the Boreal and Tethyan oceanic currents, such as the southward extension of cooler water masses (Voigt and Wiese, 2000). Lower organic productivity in surface water may be induced by these changes in ocean circulation and were recorded in sediments by an important decrease in $\delta^{13}\text{C}$.

The upper part of the Turonian and the Lower Coniacian show relatively high and stable $\delta^{13}\text{C}$. A return of high organic and calcium carbonate productivities may explain this trend. Maximum bioturbation, observed in the chalk interval (from 448 m to 508 m), confirms the existence of optimal living conditions throughout the water column.

5.4 Oxygen isotopes and global climate changes

As previously mentioned, the oxygen isotope ratios ($\delta^{18}\text{O}$) in the Craie 701 borehole present a strong variability making their interpretation complicated. The two main factors affecting $\delta^{18}\text{O}$ in marine carbonates are the temperature and salinity of the seawater. In the case of biogenic carbonates, the influence of the metabolic processes involved in the production of CaCO_3 minerals (vital effect) is added. Due to the strong thermal dependency of $\delta^{18}\text{O}$, this parameter measured in bulk carbonate has often been considered to only represent the progression of recrystallisation during burial diagenesis. Over

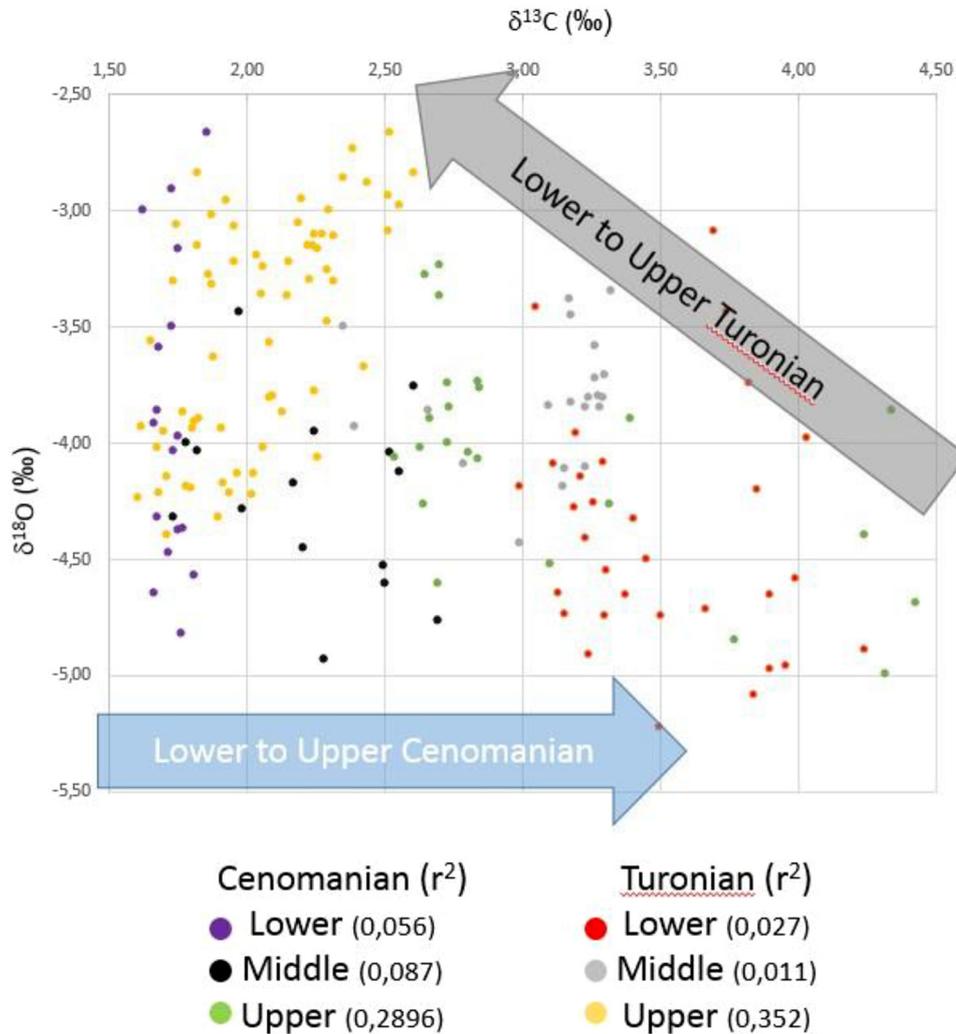


Fig. 8. $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ cross-plot from bulk rock carbonate samples from the studied Craie 701 borehole. The correlation coefficients are reported for the different time interval. The global r^2 is 0.1651.

the past 30 years, numerous studies have shown that this is not the case and that burial diagenesis does not obliterate the original primary record of the physicochemical conditions prevailing at the time of deposition. For the chalk facies, the same result was demonstrated early on by Scholle and Arthur (1980) and, more recently, on the Craie 701 borehole by Chenot *et al.*, 2016. Recent data obtained by separation of the various carbonate producers (Minoletti *et al.*, 2005, 2007; Bojanowski *et al.*, 2017; Tremblin and Minoletti, 2018) show that the evolution of the $\delta^{18}\text{O}$ values of the bulk carbonate is similar to that of the different biogenic fractions (foraminifera, nannofossils) or the fraction of non-obvious origin (so-called micarb). Moreover, these results show that $\delta^{18}\text{O}$ variability depends much more on the fluctuations of the relative percentages of the different producers (vital effect, different depths for the environments of organisms etc.) than on diagenetic effects.

In the Craie 701 borehole, no significant changes in fossil forms are observed in the chalk deposits on a large scale but, not having any data on the relative proportion of foraminifera,

nannofossils and micarbs in the studied samples, we have chosen to take into account only the medium-term evolution of the $\delta^{18}\text{O}$ trends. Relative to the diagenesis, in the chalk part (Turonian) of the core, Lasseur (2007) considered it to remain constant as was already demonstrated by Scholle and Arthur (1980) for the European outcrops. In contrast, for the grey limestone from the Cenomanian, the impact of the diagenetic processes of cementation and recrystallisation during burial cannot be excluded, especially since the absolute values of the $\delta^{18}\text{O}$ in this level are low (close to -5‰ , Fig. 2). Nevertheless, we can see on a $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ cross plot (Fig. 9), that there is no correlation ($r^2 = 0.16$ for all data and r^2 less than 0.3 for the Cenomanian sample) between the two signals. Chenot *et al.* (2016) and Le Callonnec *et al.* (2000) previously concluded that only the chalk at the top of the Poigny borehole had been altered by meteoric waters. This implies that diagenesis under the influence of groundwater is limited. In the case of strong diagenesis control, the $\delta^{13}\text{C}$ of cement would become more depleted due to the oxidation of organic matter within sediments and, in the same way, the $\delta^{18}\text{O}$ would be lower due

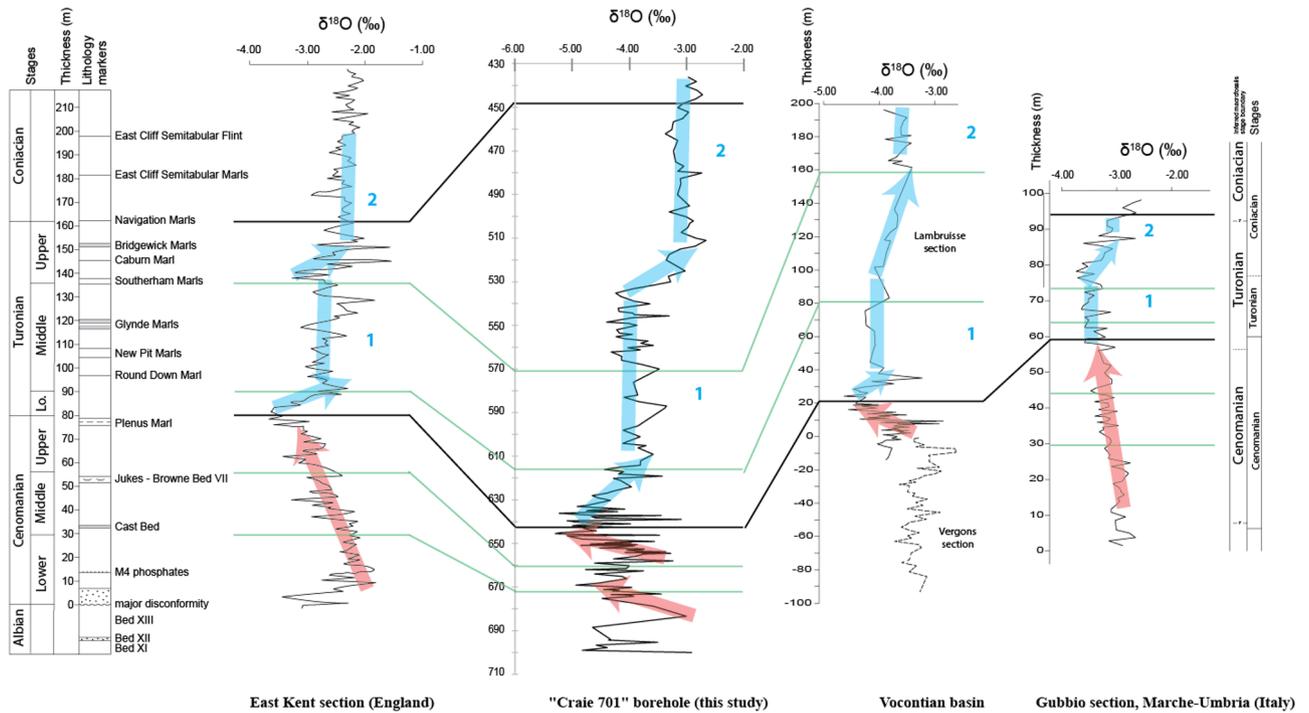


Fig. 9. Correlation of the East Kent section (Jenkyns *et al.*, 1994), Craie 701 borehole, Vocontian Basin sections (Takashima *et al.*, 2009; Gyawali *et al.*, 2017) and the Gubbio succession (Jenkyns *et al.*, 1994) Cenomanian-Turonian $\delta^{18}\text{O}$ curves.

to meteoric pore water cementation at an elevated temperature. So, even in Cenomanian facies, the $\delta^{18}\text{O}$ variations can be explained, to a large degree, as primary environmental signal changes (*i.e.*, seawater temperature and/or continental freshwater supplies).

The $\delta^{18}\text{O}$ trends of the different sections show a consistent evolution (Fig. 9), from the Cenomanian to the Turonian-Coniacian boundary. Since no $\delta^{18}\text{O}$ data is available from the Culver Cliff section, data from the East Kent section are used (Jenkyns *et al.*, 1994), which is located a little further north on the east coast of England. During the Late Cenomanian, a decrease in the $\delta^{18}\text{O}$ trend is observed, leading to the lowest isotopic values before the Cenomanian-Turonian boundary (Fig. 8). A global warming during the transition from a “warm greenhouse” (from Early Albian to Early Cenomanian) to a “hot greenhouse” (Middle Cenomanian) may explain this isotopic trend (Jenkyns *et al.*, 1994). This warming could be due to enhanced CO_2 emission in the atmosphere linked to several volcanic eruptions in the Caribbean, Ontong Java and Manihiki Plateaus (Ando *et al.*, 2009; Selby *et al.*, 2009; Ando *et al.*, 2010; Jenkyns, 2010; Du Vivier *et al.*, 2015; Nuñez-Useche *et al.*, 2016). The increase in the carbonate $^{87}\text{Sr}/^{86}\text{Sr}$ ratio from the Early Albian (0.7072) to Late Cenomanian (0.7075; Bralower *et al.*, 1997; Monnet, 2009) is consistent with an increase in ocean crust production during this period. The $\delta^{18}\text{O}$ variations in some sections have shown a brief cooling during the global warming of OAE 2 (Morel, 1998; Jarvis *et al.*, 2011; Grosheny *et al.*, 2017; Jenkyns *et al.*, 2017; Desmares *et al.*, 2019) but this event is absent in the chalk of the Craie 701 borehole.

During the Turonian, the $\delta^{18}\text{O}$ data show a progressive increase in two successive steps (Figs. 2 and 9) that seem to correspond to a long-term climatic cooling, as has been recorded in England (Jenkyns *et al.*, 1994). Several macrofaunal migrations in the Turonian were related to a climatic cooling due to a change in ocean circulation and a major regression in the Late Turonian (de Graciansky *et al.*, 1987; Clarke and Jenkyns, 1999; Stoll and Schrag, 2000; Voigt, 2000; Voigt and Wiese, 2000; Voigt *et al.*, 2004; Jarvis *et al.*, 2015).

Possible polar ice-sheet accumulation and glacio-eustatic effects have also been suggested (Stoll and Schrag, 2000; Voigt *et al.*, 2004). The evidence comes from flora associations in the northern, high latitudes (Spicer and Parrish, 1990), $\delta^{18}\text{O}$ values in marine macrofossils from Antarctica (Pirrie and Marshall, 1990) and the oceanic distribution of ice rafted debris (Frakes and Francis, 1988).

However, several remarks or reservations should be raised. First of all, the $\delta^{18}\text{O}$ data during the Late Cenomanian have a much greater variability in the Paris Basin and the Vocontian Basin than in England and Italy. More importantly, there are large differences in the mean absolute values of the isotopic ratios recorded at different sites (Table 1).

It should be noted that the variations of the $\delta^{18}\text{O}$ at the sites correlated do not reflect a paleo-latitudinal climate control. Diagenesis cannot be mentioned. Firstly, for the same facies (chalk) of environmental and burial conditions in England and the Paris Basin, the $\delta^{18}\text{O}$ record is very different. Secondly, sediments from Umbria-Marche should be the most diagenetically altered (siliceous limestones with styloliths), but they show the highest $\delta^{18}\text{O}$, when it should be the opposite. In

Table 1. Comparison of the mean oxygen stable isotope data (‰) from the studied core, East Kent (England), Vocontian Basin and Umbria-Marche sections for the key time intervals.

| | $\delta^{18}\text{O}$ (average in ‰) | | | |
|--|--------------------------------------|------------------------|-----------------|---------------|
| | South England | South-East Paris Basin | Vocontian Basin | Umbria-Marche |
| Early Cenomanian | -2.25 | -3.8 (from -3 to -4.8) | | -3 |
| Late Cenomanian | -3 | -4 (from -3.3 to -4.8) | | -3.2 |
| Latest Cenomanian (Minimum isotope data) | -3.5 | -5.25 | -3.5 | -3.6 |
| Early Turonian (first step isotopic) | -2.75 | -4 | -4.2 | -3.5 |
| Early Turonian (second step isotopic) | -2.30 | -3.1 | -3.7 | -3.2 |

contrast, the lithological facies of the Paris Basin (soft chalk) have recorded lower $\delta^{18}\text{O}$. Therefore, we can consider that if the long-term evolution of oxygen isotopic ratios reflects warming during the Cenomanian and cooling during the Turonian, a regional paleo-environmental event must be added for the south-east part of the Paris Basin and the Vocontian Basin. That event is responsible for the variability and the lowest $\delta^{18}\text{O}$ recorded in these sections. Since these regions represent a corridor of communication between the Boreal domain and the Tethyan Ocean, we can evoke the influence of continental freshwater and/or polar water with low $\delta^{18}\text{O}$ and the competition between these waters and those of the Tethys to explain the high variability of $\delta^{18}\text{O}$.

England (close to the oceanic influence of the North Atlantic) and Umbria-Marche (in the open Tethys) would be excluded from the influence of these low $\delta^{18}\text{O}$ waters. Such mass marine-water circulation (southward or northward during the Cenomanian and Turonian) has been proposed to explain the macrofauna migrations (Voigt and Wiese, 2000) and the changes in dinoflagellate cysts and the planktonic/benthic fauna ratio (Paul *et al.*, 1994).

In detail, the Craie 701 isotopic curve (Fig. 3) shows that, during the deposition of the Plenus Marls, a clear downward $\delta^{18}\text{O}$ trend can be interpreted as a warm climatic phase. As mentioned before, this warming could be related to an acme of volcanic and hydrothermal marine activity in major Large Igneous Provinces, releasing large amounts of greenhouse gases into the atmosphere during OAE 2 (Ando *et al.*, 2009; Selby *et al.*, 2009; Jenkyns, 2010; Erba *et al.*, 2015; Nuñez-Useche *et al.*, 2016). Such climatic warming with minimal vertical and latitudinal thermal gradients during OAE 2 has been suggested by numerous authors (Huber *et al.*, 1999; Jenkyns, 1999; Voigt *et al.*, 2004; Forster *et al.*, 2007; Jenkyns, 2010; Aguado *et al.*, 2016).

6 Conclusions

Stable carbon isotope chemostratigraphy carried out on the Craie 701 borehole allows for a high-resolution stratigraphic framework from the Cenomanian to the Turonian-Coniacian boundary. Thus, this borehole, located in the south-east Paris Basin, represents one of the best reference sections for correlating biostratigraphic and geochemical events between the Tethyan and Boreal realms. Comparison of the Craie 701 $\delta^{13}\text{C}$ profile with those of various marine sites from northern European epicontinental seas and the Tethyan Ocean has shown similar and synchronous isotopic events which imply

global processes. In particular, the middle-term increase in $\delta^{13}\text{C}$ values (about 1.5‰ amplitude), which occurs from the Middle Cenomanian to Middle Turonian, corresponds to a global increase in organic and carbonate productivity. This event coincides with the mid-Cretaceous eustatic sea level rise.

OAE 2 is highlighted by a large, brief positive carbon isotope excursion (CIE), superimposed on the middle term trend that occurs during the Late Cenomanian. The CIE is present at all of the sites, whatever the sedimentary facies. However, its amplitude is variable from one site to another: it is higher (5.2‰) in the epicontinental sites, where anoxia is less pronounced, than in the open oceanic sites (3.2‰), where black shale intervals are recorded.

A regional and environmental modulation related to the preservation and burial of organic matter is thus superimposed on the global processes. The fluctuations of the calcium carbonate content in the latest Cenomanian sediments are likely to be linked to the massive volcanic CO_2 degassing in the atmosphere and the acidification of seawater.

Variations in $\delta^{18}\text{O}$ suggest that the Cenomanian-Turonian boundary represents a major turning point in the climatic history of the Earth, peaking at the OAE 2. In addition, $\delta^{18}\text{O}$ data provide evidence of Turonian climate deterioration, characterised by synchronous stepped episodes of cooling throughout Europe, during the Early and Late Turonian in particular.

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