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New insights on the Late Paleocene – Early Eocene dinoflagellate cyst zonation for the Paris and Dieppe basins

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Abstract - The Anglo-Belgo-Paris Basin, historical cradle of the Paleogene stratigraphy since the 19th century, is known by the presence of very specific so-called "Sparnacian" deposits (very diverse and laterally highly variable, predominantly lagoonal to terrestrial facies), which encompass the short stratigraphic interval of the Paleocene-Eocene Thermal Maximum (PETM). Due to the insufficient nature of the paleontological record, the "Sparnacian" succession of the Paris and Dieppe-Hampshire basins still needs to be robustly chronostratigraphically correlated with other Paleogene records worldwide. In order to refine the stratigraphy of the Thanetian-Lower Ypresian succession in northern France a number of cores and outcrop sections have been investigated palynologically. As a result, an updated version of the dinoflagellate cyst zonation for the Paris and Dieppe basins is proposed and contains six new or revised biozones for this stratigraphical interval: Alisocysta margarita, Apectodinium hyperacanthum, Apectodinium-acme, Biconidinium longissimum-acme, Dracodinium astra, and Axiodinium lunare/Stenodinium meckelfeldense. Based on combined bio-, litho- and chemostratigraphic data, it appears that the dinocyst assemblages, corresponding to the PETM event interval ("Sparnacian" deposits, Soissonnais and upper Mortemer formations), are characterized by an acme of Apectodinium spp. (70–98%) in both basins, sometimes alternating with an acme of a few gonyaulacoid groups in the Dieppe Basin. Dinocyst assemblages from the PETM interval contain a significant number of atypical, longer specimens of Apectodinium parvum, which could represent an ecological onshore substitute for Axiodinium augustum in the Paris and Dieppe-Hampshire basins. The establishment of a new Biconidinium longissimum-acme Zone suggests that the stratigraphic hiatus previously inferred within this sequence in the Paris Basin does not exist.

Keywords: dinoflagellate cysts / Late Paleocene / Early Eocene / "Sparnacian" / zonation / Paris and Dieppe-Hampshire basins

Résumé – Nouveau regard sur la zonation de kystes de Dinoflagellés du Paléocène supérieur – Éocène basal des bassins de Paris et Dieppe. Le Bassin anglo-belgo-parisien, berceau historique de la stratigraphie du Paléogène depuis le XIX^e siècle, est connu pour la présence de dépôts très spécifiques, nommés sparnaciens (faciès très divers, majoritairement continentaux et lagunaires, avec de nombreuses variations latérales), qui contiennent le court intervalle stratigraphique du Maximum Thermique de la limite Paléocène-Éocène (*Paleocene-Eocene Thermal Maximum* ou PETM en anglais). En raison de l'enregistrement paléontologique insuffisant, la succession sparnacienne des bassins de Paris et de Dieppe-Hampshire nécessite toujours une corrélation robuste avec les autres enregistrements mondiaux. Afin d'affiner la stratigraphie de la succession du Thanétien-Yprésien inférieur du Nord de la France, une série de forages et d'affleurements a été étudiée sur le plan de la palynologie. Il en résulte une version mise à jour de la zonation des kystes de Dinoflagellés pour les bassins de Paris et de Dieppe, qui contient six biozones nouvelles ou révisées pour cet intervalle stratigraphique : *Alisocysta margarita, Apectodinium hyperacanthum, Apectodinium-*acme, *Biconidinium longissimum*-acme, *Dracodinium astra*, et *Axiodinium lunare/Stenodinium meckelfeldense*. Fondée sur l'intégration de

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données bio-, litho- et chemostratigraphiques, il y apparaît que les assemblages de dinokystes correspondant à l'intervalle du PETM (dépôts sparnaciens de la Formation du Soissonnais et du sommet de la Formation de Mortemer), sont caractérisés par un acmé d'*Apectodinium* spp. (70–98%) dans les deux bassins, alternant parfois avec un acmé de quelques groupes de gonyaulacoïdes dans le bassin de Dieppe. Les assemblages de dinokystes de l'intervalle du PETM contiennent un nombre significatif de spécimens atypiques, plus longs, d'*Apectodinium parvum*, qui pourraient représenter un substitut écologique côtier de l'espèce *Axiodinium augustum* dans les bassins de Paris et de Dieppe-Hampshire. L'établissement de la nouvelle zone d'acmé à *Biconidinium longissimum* suggère l'absence d'un important hiatus stratigraphique auparavant interprété pour le bassin de Paris.

Mots clés : kystes de Dinoflagellés / Paléocène supérieur / Éocène inférieur / "Sparnacian" / Bassin parisien / Bassin de Dieppe-Hampshire

1 Introduction

The Paris Basin is where the Paleocene Epoch and the "Sparnacian Stage" were originally defined and introduced in the 19th century (Dollfus, 1880; Schimper, 1874). Until the end of the 20th century, the Upper Paleocene-Lower Eocene succession considered here included three different lithologies, easily distinguishable. Marine glauconiferous sandy units, broadly referred to the Paleocene "Sables de Bracheux" and the Eocene "Sables de Cuise", bracket a poorly understood lithologic body composed by terrestrial and brackish clays, limestones, sands and lignites (mostly containing organic matter) and widely referred to as "Argiles à Lignites" (Aubry et al., 2005, p. 65). This lithologic complex of littoral to terrestrial deposits with particular facies and faunas, sandwiched between marine Thanetian and "Cuisian" sands, was considered in the 19th century sufficiently distinctive as to erect a new, Sparnacian stage by Dollfus (1880). As was highlighted by Aubry et al. (2005, p. 65), whereas the chronostratigraphic connotation of the "Sparnacian Stage" has been controversial since its initial definition, modern studies of the Late Paleocene-Early Eocene interval have revealed that the so-called Sparnacian deposits encompass a remarkable and short (~200 kyr; Dickens, 2000) episode in Cenozoic history, the Paleocene-Eocene Thermal Maximum (PETM). Nevertheless, the "Sparnacian" deposits, diachronous across the Paris and Dieppe basins and represented by diverse and laterally highly variable, predominantly lagoonal and non-marine facies, are still insufficiently documented and chronostratigraphic correlation with other Paleogene records worldwide needs to be updated.

Based on extensive fieldwork and integration of litho- and biostratigraphy in the Paris and Dieppe basins (Aubry *et al.*, 2005), M.-P. Aubry, M. Thiry, Ch. Dupuis and W. Berggren introduced a formal lithostratigraphic framework for the Paleocene-Lower Eocene succession in northern France. Since 2005, the Paleocene-Lower Eocene succession in the Paris and Dieppe (French part of the Dieppe-Hampshire) basins has comprised four distinct groups of lithostratigraphic units (from bottom to top, Fig. 1):

- the Vigny Group the Lower Paleocene marine limestones ("Calcaire de Vigny", "Calcaire de Meudon", etc.) and terrestrial marls ("Marnes de Meudon") in the Paris Basin, unconformably overlying the Campanian Chalk;
- the Vesles Group marine glauconitic sandy units of Thanetian age (Moulin Compensé, Châlons-sur-Vesles and

Bracheux formations), expanded from Dieppe to Paris and Reims;

- the Mont Bernon Group (Mortemer, Vaugirard, Soissonnais and Epernay formations), broadly extended across the Paris and Dieppe basins, was introduced by Aubry *et al.* (2005) to formalize the so-called "Sparnacian" clays and lignite-bearing clays with intercalated lacustrine limestone and marls, littoral sands and brackish clays including coquinas. These sediments are diachronous across the Paris Basin and embrace the P/E boundary and Early Eocene;
- the Montagne de Laon Group (marine calcareous sandy Mont-Notre-Dame, Cuise and Laon formations) of younger Ypresian age.

As was underlined by Aubry *et al.* (2005, p. 88), correlations within the Mont Bernon Group are problematic even within distances of a few tens of kilometers as a consequence (1) of abrupt lateral and vertical facies variations and especially (2) because these abrupt changes in facies result in an irregular distribution of biostratigraphic markers. Thus, calcareous nannoplankton is virtually absent in the Mont Bernon Group sediments; it is known only from the underlying Thanetian deposits (NP8–9 zones interval) and from the overlying Varengeville Fm (NP11 Zone). Consequently, the "Sparnacian" sediments are only provisionally attributed to the upper NP9–lower NP10 zones interval.

For over 50 years, since the two important papers of Châteauneuf and Gruas-Cavagnetto (1978) and Costa et al. (1978) appeared, dinoflagellate cyst stratigraphy has played an important part in clarifying the correlations between the Upper Paleocene-Lower Eocene succession in northern France and the other parts of the former North Sea Basin. However, until now the dinocyst data from the Paris and Dieppe basins have been sparse, mostly focused on paleoenvironmental reconstructions and only a limited amount of data is useful for robust stratigraphic interpretations. As a result, Aubry et al. (2005, p. 88) concluded that the Mont Bernon Group ("Sparnacian" deposits) cannot be described in terms of biozonal succession, and biozonal boundaries have not been delineated in any of its formations due to the sporadic distribution of fossil groups in highly variable lithologies, reflecting deposition in unstable marginal environments.

Focusing on producing a new high-resolution study of the Mont Bernon Group and its relationship with the PETM and its associated carbon isotope excursion (CIE), a number of old and new Paleocene-Lower Eocene BRGM boreholes and key-outcrops have been investigated palynologically and

Simplified lithostratigraphic framework for
the Upper Paleocene-Lower Eocene deposits of the Paris Basin
(Aubry et al., 2005, modified)

Chateauneuf & Gruas-Cavagnetto (1978) Dinocyst zones in the Paris Basin

PARIS B		
Montagne de Laon Group	Laon Fm.	W6
	Cuise Fm.	W5 W4 W3 (W. meckelfeldensis)
	Mont-Notre-Dame Fm.	W2 (<i>W. astra</i>) hiatus
Mont Bernon Group	Soissonnais Fm.	
	Vaugirard Fm.	W1 (A. homorphum)
	Mortemer Fm.	
	Bracheux Fm.	
VESLES GROUP	Chalons-sur-Vesles Fm.	
	Moulin Compense Fm.	
VIGNY GROUP	no formation defined	

Fig. 1. Simplified lithostratigraphic framework for the Upper Paleocene-Lower Eocene deposits of the Paris Basin (modified from Aubry *et al.*, 2005), combined with the previous Paris Basin dinoflagellate cyst zonation of Châteauneuf and Gruas-Cavagnetto (1978).

chemostratigraphically over the last 13 years as a part of the BRGM PaleoScene and "Paléosurface éocène-PETM" research projects (included in the "Référentiel géologique de la France" (RGF) Program), resulting in a significant amount of new dinocyst records. The purpose of the present paper is to refine the high-resolution stratigraphic framework for the Upper Paleocene-Lower Eocene succession in the Paris and Dieppe basins by introducing an updated dinoflagellate cyst zonation, based on our new palynological data.

2 Previous studies

In the last century dinoflagellate cysts have been studied from the Paleogene sediments in northern France by J.J. Châteauneuf and C. Gruas-Cavagnetto (Bignot et al., 1981; Châteauneuf, 1968, 1971, 1976, 1980; Châteauneuf and Fauconnier, 1977; Châteauneuf and Gruas-Cavagnetto, 1968, 1978; Châteauneuf and Trauth, 1972; Gruas-Cavagnetto, 1968, 1970, 1974, 1976a, 1976b, 1976c, 1978; Gruas and Bignot, 1985; Gruas-Cavagnetto et al., 1980) and recorded from the most part of the lagoonal and marine Paleogene formations from the Sables de Bracheux up to the Sables de Fontainebleau. According to Châteauneuf and Gruas-Cavagnetto (1978), the Paleogene of the Paris Basin can be divided into 14 dinoflagellate zones (W1-W14, Late Paleocene-Early Oligocene) based on the subfamily Wetzelielloideae (Fig. 2). Together with the similar zonations of Costa and Downie (1976) for the Late Paleocene-Early Oligocene of southern North Sea Basin and of Caro (1973) for the Paleocene-Early

Eocene of Spanish Pyrenees, the Paris Basin dinoflagellate zonation represented the first important step in the development of the Paleogene dinoflagellate cyst biostratigraphy.

Dinoflagellate studies from the so-called "Sparnacian" sediments in the Paris and Dieppe basins started in the 1960s. As a result, a number of key-outcrops and cores have been investigated with quite different sampling spacing: Guitrancourt Quarry, Le Meux and Vieux Moulin (Gruas-Cavagnetto, 1968); localities Sinceny core (Gruas-Cavagnetto, 1968); Montjavoult, Le Tillet and Ludes cores (Châteauneuf and Gruas-Cavagnetto, 1968); Les Hogues core (Châteauneuf, 1971); Mont Chenot outcrops (Gruas-Cavagnetto, 1974); Cuise-la-Motte and La Defense cores (Gruas-Cavagnetto, 1976a, 1976b); Châlons-sur-Vesles outcrops (Gruas-Cavagnetto, 1976c); Montagne de Reims outcrops (Gruas-Cavagnetto et al., 1980); Soissons outcrops (Bignot et al., 1981); Saint-Valery-sur-Somme outcrops and core (Dupuis et al., 1982); Sotteville-sur-Mer cliff section (Gruas and Bignot, 1985); and the Cap d'Ailly cliff section (Dupuis et al., 1998a, 1998b).

According to Schuler *et al.* (1992), the lowermost association, recognized in the Paris Basin within the Tuffeau de la Fère and Sables de Bracheux, was not defined as a zone and only presumably attributed to the European D4 Zone, and contained species *Alisocysta circumtabulata*, *Deflandrea oebisfeldensis* and *Hafniasphaera septata*. In the Thanetian-Early Ypresian interval of the Paris Basin Châteauneuf and Gruas-Cavagnetto (1978) have established three main dino-flagellate zones (Fig. 1):

AGES	ETAGES	FORMATIONS ESPECES WETZELIELLACEAE	APECTODINIUM HOMOMORPHUM APECTODINIUM HOMOMORPHUM SUBSP. TESSELATUM APECTODINIUM PARVUM APECTODINIUM CF. SUMMISSUM WETZELIELLA ASTRA WETZELIELLA ASTRA WETZELIELLA ASTRA KISSELEVIA CRASSORAMOSA KISSELEVIA TENUIVIRGULA DRACODINIUM SIMILIS DRACODINIUM CF. VARIELONGITUDIS WETZELIELLA ARTICULATA	ZONATION	STANDARD ZONATION
	SABLES FORMATION			VARIELONGITUDIS ZONE	W 5
			SIMILIS ZONE	W 4	
Z	- IISIE			MECKELFELDENSIS ZONE	W 3
ERDI	0			ASTRA ZONE	W 2
	SPARNACIEN	FAUSSES GLAISES ARGILES ET LIGNITES		HOMOMORPHUM ZONE	W 1
PALEOC ENE	THANE TIEN	SABLES DE BRACHEUX			

Fig. 2. Paleocene-Early Eocene part of the previous dinoflagellate cyst zonation for the Paris Basin as published originally by Châteauneuf and Gruas-Cavagnetto (1978).

- W1 (Apectodinium homomorphum) Zone from the lowermost (LO) occurrence of Apectodinium spp. to the LO of Wetzeliella astra;
- W2 (Wetzeliella astra) Zone from the LO of W. astra to the LO of Wetzeliella meckelfeldensis;
- W3 (Wetzeliella meckelfeldensis) Zone from the LO of W. meckelfeldensis to the LO of Dracodinium simile.

Based on the study of the key-sections, Châteauneuf and Gruas-Cavagnetto (1978) then concluded that the bulk of the "Sparnacian" deposits, including the Sables de Sinceny, Argiles à Lignites du Soissonnais and Fausses Glaises du Vexin (=Soissonnais Fm) correspond to the W1 Zone, while the Fausses Glaises de Paris (=Epernay Fm) and Sables d'Auteuil belong to the W3 Zone. Furthermore, Châteauneuf and Gruas-Cavagnetto (1978) noted that the Soissonnais Formation revealed dinocyst assemblages extremely rich in *Apectodinium* spp. (up to 80–90%).

It can be noted that, while dinoflagellate *Wetzeliella astra* (W2) and *Wetzeliella meckelfeldensis* (W3) zones are still used as references and are present in different dinoflagellate zonations for the North Sea Basin, eastern Peri-Tethys and Western Siberia, the *Apectodinium homomorphum* Zone in terms of Costa and Downie (1976) and Châteauneuf and Gruas-Cavagnetto (1978) is now subdivided into three successive zones (Iakovleva, 2017; Iakovleva and Aleksandrova, 2013; Köthe, 2012; Mudge and

Bujak, 1996; Powell, 1992): Apectodinium hyperacanthum, Apectodinium (=Axiodinium) augustum and Glaphyrocysta ordinata/Deflandrea oebisfeldensis. The A. augustum Zone, established between the lowermost and highest occurrences of the nominative taxon, is characterized by the oldest acme of Apectodinium spp., occurring ~at the Paleocene-Eocene boundary defined by the CIE. As was rightly noted by Aubry et al. (2005, p.89), it is problematic to delineate the A. augustum Zone in the Paris Basin because the nominative species has not been recorded here. The similar virtual absence of Apectodinium augustum in the adjacent London Basin was explained by its restriction to more offshore marine conditions (Powell et al., 1996). As a result, Powell et al. (1996) proposed to use the beginning of the Apectodinium-acme (>35% of dinocyst assemblage) to recognize the base of the A. augustum Zone. However, in 2005, Aubry et al. noticed (p. 89) that (1) the Apectodinium-acme was not unique to the Paleocene-Eocene boundary, (2) dinocyst counts were not available for all localities in the Paris Basin where Apectodinium species were recorded, (3) dinocyst assemblages were often rare and of low diversity in the shallow marine deposits of the Mont Bernon Group.

With regard to younger lowermost Eocene sediments, Aubry *et al.* (2005) concluded that there may be an indication of a stratigraphic gap in northern France based on the similarity of the Paris and London basins, the absence of *Leiosphaeridia*acme or *Deflandrea oebisfeldensis*-abundance in the dinocystbearing deposits of the Paris Basin, which are known from the Harwich Formation in the North Sea and southern England and characterize the *Glaphyrocysta ordinata* Zone (Mudge and Bujak, 1996; Powell *et al.*, 1996).

3 Material and methods

Our updated version of dinoflagellate cyst zonation of the Late Paleocene-Early Eocene interval for northern France is based on the study of ~600 palynological samples, investigated during the last 13 years under the scope of the BRGM PaleoScene and "Paléosurface éocène-PETM" research projects from more than 35 new or already well-known Paleocene-Lower Eocene key localities and boreholes (Fig. 3). More precisely they are (i) the cores Siège-Madame and Phare d'Ailly and outcrops Cap d'Ailly, Blanc Pâtis, Vasterival, Sotteville-sur-Mer and Criel on the Normandy coast (Dieppe Basin); (ii) the cores Therdonne, Le Tillet, Sinceny, Noyon, Cuise-la-Motte, Try, Venteuil, Montmacq, Porquericourt and outcrops Lihons, Clairoix, Rivecourt, Holnon, Laon, and Brimont for the Paris Basin; (iii) and the core Bois-de-Ville and outcrops Wizernes, Flines-lez-Râches and Boiry-Notre-Dame for the Belgian Basin, and the cores Avesnois-007 (Locquignol), Avesnois-031 (Viesly), and Vertain for the transitional zone between the Paris and Belgian basins. Additionally, for interregional correlation purposes, we use our unpublished dinocyst data from the BGS (British Geological Survey) cores from the London and Hampshire basins: the London Jubilee Line 404T, Shamblehurst Lane, Shotley Gate and Stanford-Le-Hope; and, finally from the BGS 81/46A core drilled in the British sector of the North Sea Basin. See the List of locations of the principal studied sections in Supplementary Material. Our study is also the first attempt to make a first-order calibration between dinocyst and isotopic data from the Late Paleocene-Early Eocene interval in the shallow marine to lagoonal settings of the Paris and Dieppe basins.

In the scope of our research, dinoflagellate cysts have been investigated from the following lithostratigraphic units (from base to top):

- the Vesles Group: (a) the Châlons-sur-Vesles Fm (6 m thick) white and yellow, fine, glauconitic sand with abundant molluscan shells; it comprises the "Sables de Dieppe", "Sables de Châlons-sur-Vesles", "Sables de Montjavoult", "Sables du Tillet" and corresponds to nannoplankton NP8 Zone (Aubry, 1983, 1986; Dupuis and Steurbaut, 1987; Steurbaut, 1998); (b) the Bracheux Fm (4.5–30 m) coarse, glauconitic, calcareous sand; it includes the "Sables de Bracheux" and "Sables de Criel" and corresponds to nannoplankton NP9a Subzone (Aubry, 1983, 1986; Aubry *et al.*, 2005; Bignot *et al.*, 1994; Dupuis and Steurbaut, 1987; Steurbaut, 1998);
- the Mont Bernon Group: (a) the Mortemer Fm (~3–15 m), which consists of mainly terrestrial limestones and marls ("Calcaire d'Ailly", "Marnes à Rognons", etc. members), rich in ostracods and charophytes (part of the *Peckichara disermas* Zone, Riveline, 1986); (b) the Vaugirard Fm is composed of clays ("Argiles Plastiques" in Cuvier and Brongniart, 1811), and includes the Limay, Provins, Meudon and other members, it corresponds to the charophyte *Peckichara disermas* Zone; (c) the Soissonnais Fm (~8–12 m) is quite diverse lithologically and includes dark clays, silts, sands, shelly laminae or beds and lignite

beds ("Argiles du Soissonnais à Lignites" of Brongniart, 1829) deposited in lacustrine, swamp and shallow-marine conditions. Regionally the Soissonnais Fm is divided in a number of members, including the "Sables et Argiles à Ostracodes et Mollusques" (SAOM) in Bignot (1965) and Craquelins members in the Dieppe Basin, and the Vauxbuin, Vexin and others in the Paris Basin; (d) the Epernay Fm (exposed only in the eastern part of the Paris Basin, up to 20 m thick) includes clays, sands and lignites;

• the Montagne de Laon Group deposits (mostly calcareous and glauconitic sands) are widely exposed in the Paris Basin and are divided successively into the Mont-Notre-Dame (Sinceny, "Sables de Laon", "Sables d'Aizy" members), Cuise and Laon Fms. The Varengeville Formation in the Dieppe Basin is preliminary related to the Montagne de Laon Group, while it clearly differs lithologically and is mostly composed of clays (Aubry *et al.*, 2005). The upper Varengeville Fm ("Argiles et Sablons" Member) and "Sables d'Aizy" Member are attributed to the nannoplankton NP11 Zone, while the "Sables de Cuise" Member questionably corresponds to the lower NP12 Zone (Aubry, 1983, 1986). The Montagne de Laon Group is overlain by the "Glauconie Grossière" of Lutetian age (Aubry *et al.*, 2005).

According to recently obtained high-resolution geochemical data (Garel, 2013; Iakovleva et al., 2014a, 2014b; Quesnel et al., 2009, 2011, 2014; Smith et al., 2011, 2014; Storme 2013; Storme et al., 2012), it appears that the onset of the CIE corresponding to the PETM, is clearly delineated within the Mortemer Fm, which was deposited in mostly terrestrial environments (marsh, pond, lake, fluvial channels, flood plain etc.). The CIE continues until the top of the littoral-lagoonal Soissonnais Fm (Muirancourt and Vauxbuin members in the Paris Basin and the SAOM and Craquelins members in the Dieppe Basin). Within the CIE-event interval the $\delta^{13}C_{or}$ values vary between -25 and -32% PDB (Pee Dee Belemnite) with the most negative $\delta^{13}C_{or}$ values between -27 and -32%depending on the localities and depositional environments, while the $\delta^{13}C_{or}$ values below and above the CIE extend from -22 to 24‰. The lowermost unit (postdating the PETM) of the Mont Notre Dame Fm (Sinceny Member) in the Paris Basin is characterized by very homogeneous $\delta^{13}C_{org}$ values between -24 and -25% PDB (Quesnel et al., 2011).

In the present work we use the terms LO (lowermost occurrence), HO (highest occurrence) and acme to designate significant dinocyst "events" (datums). Dinoflagellate cyst taxonomy follows Williams *et al.* (2017). Recently, for the subfamily Wetzelielloideae, a new systematics, introducing a number of new genera, was proposed by Williams *et al.* (2015). Because the species of Wetzelielloideae were the nominative taxa in the first Paris Basin dinoflagellate zonation of Châteauneuf and Gruas-Cavagnetto (1978), we mention below the old generic names in parentheses to simplify the understanding of the emendated species names.

The chronostratigraphic age is according to Ogg *et al.* (2016). Palynomorphs were concentrated using standard palynological techniques of the British Geological Survey (Riding and Kyffin-Hughes, 2004) and Liège University (Belgium, Roche *et al.*, 2008). These are: (1) dissolution of carbonates



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Fig. 3. Simplified geological map showing the distribution of Cenozoic sedimentary rocks in the SE part of the former North Sea Basin with location of studied sections (modified after IGME, 2005 and Quesnel *et al.*, 2009).

and silicates by HCl and HF acid digestion; (2) sieving between 106 and 10 μ m; (3) neutralization with distilled water and centrifugation; then mounting of the remaining residues on the slides. A slight acetolysis was performed for the samples richer in amorphous organic matter.

Palynological material from the Paris, Dieppe and London basins, containing the dinoflagellate cyst zonal assemblages, is stored in the BRGM, Orléans, France. The raw palynological data (containing ~200 taxa of dinoflagellate cysts, acritarchs and prasinophytes) from the BRGM and BGS sections are available in Supplementary Material.

4 Results

Stratigraphic distribution of the key dinocyst events from studied sections in northern France and adjacent areas has enabled the development of a precise dinoflagellate zonation scheme for the Late Paleocene-Early Eocene of the Paris and Dieppe basins. Based on our palynological counting and on a number of noticeable lithostratigraphic features in the Dieppe and Paris basins, we present here a new updated biozonation with the lithostratigraphic logs for each basin (Fig. 4). The most typical dinoflagellate cysts are shown on Plates 1, 2 and 3.

It should be noted that the Moulin Compensé Formation (6–7 m thick), the lowermost Upper Paleocene unit in northern France, has a restricted geographical distribution. It is composed of glauconitic, clayey, calcareous silts or sands and assigned to the nannoplankton NP6–7 zones (Aubry *et al.*, 2005; Janin and Bignot, 1993; Steurbaut, 1998), but was not seen in the sections we have studied. As a result, the characteristics of the dinocyst assemblage from the lowermost Thanetian sediments in this region remains unclear.

4.1 The Alisocysta margarita Zone (Paris Basin)

Definition: interval from the LO of *Deflandrea denticulata* to the LO of *Apectodinium homomorphum*.

Diagnostic events: besides *D. denticulata*, the species *Alisocysta* sp.2 *sensu* Heilmann-Clausen (1985) occurs also at the base of this zone. The species *Biconidinium longissimum* occurs, while *Alisocysta margarita* and *Tanyosphaeridium xanthiopyxides* disappear within this interval. Characteristic species of this zone are *Phthanoperidinium crenulatum*, *Conneximura fimbriata*, *Melitasphaeridium pseudorecurvatum*, *Hystrichosphaeridium tubiferum*, *Trigonopyxidia ginella*, *Palaeotetradinium minusculum*, *Palaeocystodinium lidiae*, *Glaphyrocysta divaricata*, *Glaphyrocysta pastielsii*, as well as abundant *Areoligera gippingensis*-group (*A. coronata*, *A. gippingensis*, *A. medusettiformis*, *A. senonensis*).

Reference section: Châlons-sur-Vesles Fm (31.12–25.19 m depth), Noyon core, Oise Department (former Picardy, now Hauts-de-France Region).

Calibration: the *Alisocysta margarita* Zone corresponds to the NP8 nannoplankton Zone interval (Dupuis and Steurbaut, 1987).

Chronostratigraphic Age: Thanetian (~58.5–56.5 Ma).

The *Alisocysta margarita* Zone is also established in the Paris Basin within the Châlons-sur-Vesles Fm from the presently unexposed base of the Rivecourt section (Sables de Châlons-sur-Vesles Member); in the transitional zone between the Paris and Belgian basins within the Wizernes Tuffeau Member in the Wizernes and Boiry-Notre-Dame sections and within the Grandglise Member in the Flines-lez-Râches section.

The *A. margarita* Zone, established in the Paris Basin, corresponds to the homonymous zone in southern England (Powell *et al.*, 1996) and is equivalent to the Viborg 4-lowermost Viborg 5 zones in Denmark (Heilmann-Clausen, 1985). According to our unpublished data from the south of England, the *A. margarita* Zone interval is also recognized within the Thanet Sand Fm in the BGS London Jubilee Line 404T and Stanford-Le-Hope cores.

4.2 The Apectodinium hyperacanthum Zone (Paris and Dieppe basins)

Definition: interval from the LO of *Apectodinium homomorphum* to the LO of the acme of *Apectodinium* spp.

Diagnostic events: the species *Apectodinium quinquelatum, A. summissum, A. parvum* occur at the base of this zone, while *Apectodinium paniculatum, A. folliculum* and *A. hyperacanthum* occur first within this zonal interval.

Reference section in the Paris Basin: Châlons-sur-Vesles Fm (uppermost Le Tillet Sand Member) – Bracheux Fm (184.35–166.0 m depth), Le Tillet core, Oise Department (former Picardy, now Hauts-de-France Region).

Reference section in the Dieppe Basin: Bracheux Fm (Criel Sand Member) (27.2–18.9 m depth), Siège-Madame core, Seine-Maritime Department, Normandy Region.

The *A. hyperacanthum* Zone is also established in the Paris Basin in the Clairoix locality, although this part of the section is now obscured at the base of the cliff (glauconitic sand of the Bracheux Fm), in the Noyon core (uppermost Châlons-sur-Vesles Fm), Cuise-la-Motte core (uppermost Le Tillet Sand Member of the Châlons-sur-Vesles Fm and Sables de Bracheux Member of the Bracheux Fm), Try core. In the transitional zone between the Paris and Belgian basins this zone is established in the Brimont outcrop section (in a silty very fine sand, unascribed to any formal lithostratigraphic unit yet), Vertain core (Vertain Crag Member), AVE-007 and AVE-031 cores (Vervins Member, Clary Clay Member and Viesly Crag Member of the Hainaut-Valenciennois Formation) and in the Boiry-Notre-Dame outcrop section.

Calibration: the *A. hyperacanthum* Zone interval corresponds to the NP9 nannoplankton Zone (Steurbaut, 1998).

Chronostratigraphic Age: Late Thanetian (~56.5–55.8 Ma).

The *Apectodinium hyperacanthum* Zone from the Paris and Dieppe basins corresponds to its homologous in southern England (Powell *et al.*, 1996) and in the central part of the North Sea (AI, unpublished data from the BGS 81/46A core), to the Viborg-5 Zone in Denmark (Heilmann-Clausen, 1985) and the P6a Subzone in the North Sea (Bujak and Mudge, 1994).



Fig. 4. New proposed Late Paleocene-Earliest Eocene dinoflagellate cyst zonation for the Paris and Dieppe basins.

4.3 The Apectodinium-acme Zone (Paris Basin)

Definition: interval from the LO of the acme of *Apectodinium* spp. (minimum 75% of total dinoflagellate cyst assemblage) to the LO of *Biconidinium longissimum*-acme.

Diagnostic events: the base of this zone is characterized by the occurrence of *Apectodinium parvum* specimens that are different from typical forms by the larger size of cyst and more developed apical, lateral and antapical horns. The species Axiodinium sparnacium, Vallodinium heilmannii, Vallodinium picardicum, Stichodinium sympagicum and Stichodinium elegantulum occur first within this zone interval (Vauxbuin Member, Soissonnais Fm).

Reference section: Soissonnais Fm (Muirancourt and Vauxbuin Members, 154.93–61 m depth), Le Tillet core, Oise Department (former Picardy, now Hauts-de-France Region).

The *Apectodinium*-acme Zone is also established in the Paris Basin in the Therdonne core (Bourguillemont Sand



Plate 1. 1: *Apectodinium parvum*; Le Tillet core, 148.6 m depth; slide MPA 62334-4; 2: *Sophismatia crassoramosa-tenuivirgula*; Siège-Madame core, 3.5 m depth; slide MPA 62290-7; 3: *Apectodinium parvum*; Sinceny core, 9.1 m depth; slide MPA 61460-3; 4: *Dracodinium astra*; Flines-lez-Râches section, sample FLA-2.99 m; slide MPA 60007-3; 5: *Glaphyrocysta* aff. *ordinata*; Siège-Madame core, 9.6 m depth; slide MPA 62290-5; 6: *Apectodinium parvum*; Try core, 6.2 m depth; slide MPA 62326-3; 7: *Apectodinium homomorphum*; Try core, 6.2 m depth; slide MPA 62326-3; 8: *Apectodinium paniculatum*; Siège-Madame core, 9.6 m depth; slide MPA 62299-4; 9, 10: *Alisocysta* sp. 2 *sensu* Heilmann-Clausen (1985); Rivecourt section, sample RIVE 2-0; slide MPA 59942-3; 11: *Apectodinium quinquelatum*; Siège-Madame core, 3.5 m depth; slide MPA 62290-5; 12: Gonyaulacoid C; Siège-Madame core, 7.8 m depth; slide MPA 62297-3; 13: *Sophismatia tenuivirgula*; Siège-Madame core, 3.5 m depth; slide MPA 62290-7.



Plate 2. 1: *Petalodinium lenisium*; Siège-Madame core, 13.0 m depth; slide MPA 62304-2; 2: *Vallodinium heilmannii*; Siège-Madame core, 13.0 m depth; slide MPA 62304-2; 3: *Stichodinium galliciense*; Siège-Madame core, 13.0 m depth; slide MPA 62304-2; 4: *Wilsonidium modicum*; Siège-Madame core, 13.0 m depth; slide MPA 62304-2; 5: *Epelidinium normandiense*; Siège-Madame core, 13.0 m depth; slide MPA 62304-3; 6: *Stichodinium prostimus*; Siège-Madame core, 13.0 m depth; slide MPA 62304-3; 7: *Axiodinium sparnacium*; Sinceny core, 7.0 m depth; slide MPA 61459-5; 8: *Stichodinium sympagicum*; Le Tillet core, 144.8 m depth; slide MPA 62331-4; 9: *Stichodinium parisiense*; Le Tillet core, 144.8 m depth; slide MPA 62331-5; 10: *Dracodinium? modestum*; Le Tillet core, 148.6 m depth; slide MPA 62334-4; 11: *Stichodinium*; Siège-Madame core, 13.0 m depth; slide MPA 62304-2; 12: *Vallodinium picardicum*; Le Tillet core, 144.8 m depth; slide MPA 62331-4; 11: *Stichodinium elegantulum*; Siège-Madame core, 13.0 m depth; slide MPA 62304-2; 12: *Vallodinium picardicum*; Le Tillet core, 144.8 m depth; slide MPA 62331-4; 11: *Stichodinium elegantulum*; Siège-Madame core, 13.0 m depth; slide MPA 62304-2; 12: *Vallodinium picardicum*; Le Tillet core, 144.8 m depth; slide MPA 62331-4.

Member, uppermost Mortemer Fm); in the Porquericourt core and in the Laon outcrop (Vauxbuin Member, Soissonnais Fm); within the interval of the Soissonnais Fm in the Sinceny core; in the Try and Venteuil cores within the uppermost Mortemer Fm and in the Soissonnais Fm (Vauxbuin Member); in the Flines-lez-Râches outcrop section (uppermost Flines-lez-Râches Member); within the Santerre Formation (Holnon Member) in the Lihons and Holnon outcrop sections.

Calibration: according to isotopic data from the Le Tillet, Try, Flines-lez-Râches, Therdonne, Sinceny, Holnon, Lihons, Laon and Porquericourt, the base of the acme of *Apectodinium* spp. corresponds to the global CIE, associated with the PETM event. The upper zonal boundary coincides with the end of the CIE.

Chronostratigraphic Age: Earliest Eocene (~55.8–55.6 Ma).

4.4 The Apectodinium-acme zone (Dieppe Basin)

Definition: interval from the LO of the acme of *Apectodinium* spp. (80–98% of total dinoflagellate cyst assemblage) to the HO of the acme of *Apectodinium* spp.

Diagnostic events: as in the Paris Basin, atypical specimens of *Apectodinium parvum* occur at the base of this zone in the Dieppe Basin. The species *Axiodinium sparnacium*, *Epelidinium brinkhuisii, Epelidinium normandiense, Petal-odinium lenisium, Stichodinium elegantulum, Stichodinium galliciense, Stichodinium prostimus, Vallodinium heilmannii, Vallodinium* sp. A, and *Wilsonidium modicum* occur within this zone interval. The acme of *Kenleyia* (up to 100%) and *Lingulodinium*-groups as well as those of gonyaulacoids of uncertain systematic affinity (probably goniodomaceans, see Plate 1, fig. 12; Plate 3, figs. 9, 14, 16, 17) are observed at the base and within the lower half of this zone.

Reference section: Soissonnais Fm (Ailly and Craquelins members, 8.5–20.0 m), Cap d'Ailly cliff section, Normandy.

The *Apectodinium*-acme Zone is also established in the Dieppe Basin within the uppermost Mortemer Fm (Siège-Madame Member) and Soissonnais Fm (SAOM, Sotteville and Craquelins members) in the Siège-Madame core and Sotteville-sur-Mer section and core; in the Vasterival (Phare d'Ailly and Craquelins Members), Blanc Pâtis (SAOM Member) and Criel (SAOM Member) outcrop sections.

Calibration: according to isotopic data from the Sotteville-sur-Mer, Ailly, Cap d'Ailly, Blanc Pâtis, Criel and Siège-Madame sections, the base of the acme of *Apectodinium* spp. corresponds to the global CIE, associated with the PETM event. The upper zonal boundary coincides with the end of the CIE.

Chronostratigraphic Age: Earliest Eocene (~55.8–55.6 Ma).

The *Apectodinium*-acme Zone from the Paris and Dieppe basins nearly corresponds to the *Apectodinium augustum* Zone in southern England (without nominate taxon, Powell *et al.*, 1996) and northern Belgium (Steurbaut *et al.*, 2003), to the Viborg-6 Zone in Denmark (Heilmann-Clausen, 1985), and to the P6b Subzone in the North Sea (Mudge and Bujak, 1996). According to our unpublished data from the south of England, the *Apectodinium*-acme Zone interval may be recognized within the Lambeth Group in the BGS London Jubilee Line

404T key-core. Thus, within the Lower Woolwich Beds *Apectodinium*-acme attains 50–75%, while Gonyaulacoid A (Plate 3, fig. 16), known from the Dieppe Basin, represents 35% of the dinoflagellate cyst assemblage; the Upper Reading Beds are characterized by the *Apectodinium*-acme (95–97%); finally, within the Upper Woolwich Beds *Apectodinium* spp. represents 70% and Gonyauacoid A – 25% of the assemblage.

4.5 The *Biconidinium longissimum*-acme Zone (Paris Basin)

Definition: interval from the LO of the acme of *Biconidinium longissimum* (20–48% of total assemblage) to the LO of *Dracodinium astra*.

Diagnostic events: the species *Stichodinium parisiense* and *Dracodinium? modestum* occur first at the base of this zone, while the species *Stichodinium prostimus* and *Petal-odinium lenisium* occur within this zone interval. The last manifestation of the *Apectodinium*-acme (up to 50%) is observed at the base of this zone.

Reference section:Mont-Notre-Dame Fm (Sinceny Member, 148.6–142.2 m depth), Le Tillet core, Oise Department (former Picardy, now Hauts-de-France Region).

The *Biconidinium longissimum*-acme Zone is also established within the Sinceny Member of the Mont-Notre-Dame Fm in the Therdonne, Sinceny and Cuise-la-Motte cores and in the Laon outcrop section.

Calibration: the *Biconidinium longissimum*-acme Zone corresponds indirectly to part of the NP10 Zone interval.

Chronostratigraphic Age: Earliest Eocene (~55.6–55.0 Ma).

The *Biconidinium longissimum*-acme Zone, established in the Paris Basin, is the chronostratigraphic analogue of the *Glaphyrocysta ordinata* Zone in southern England (Powell *et al.*, 1996), the *Deflandrea oebisfeldensis* Zone from the NW European compilation dinocyst scale (Powell, 1992) and of the Viborg-7 Zone in the Danish Basin (Heilmann-Clausen, 1985).

4.6 The *Dracodinium* astra Zone (Paris and Dieppe basins)

Definition: interval from the LO of *Dracodinium astra* to the LOs of *Axiodinium lunare* and *Stenodinium meckelfeldense*.

Diagnostic events: the species *Dracodinium lobiscum* occurs at the base of this zone. The species *Cleistosphaeridium polypetellum*, *Homotryblium tasmaniense* and *Homotryblium tenuispinosum* occur within the interval of this zone.

Reference section in the Paris Basin: Mont-Notre-Dame Fm (Sables de Laon Member, 140.0–137.0 m depth), Le Tillet core, Oise Department (former Picardy, now Hauts-de-France Region).

This zone is also established in the Paris Basin in the Venteuil Member (Mont-Notre-Dame Fm) in the Venteuil core.

Reference section in the Dieppe Basin: Varengeville Fm (Sables Fauves Member, samples 8.9–6.0 m depth), Siège-Madame core, Seine-Maritime, Normandy.

It is also established in the Dieppe Basin within the Sables Fauves Member in the Cap d'Ailly cliff section.



Plate 3. 1: *Kenleyia*-complex; Siège-Madame core, 18.4 m depth; slide MPA 62307-3; 2: *Kenleyia*-complex; Siège-Madame core, 18.4 m depth; slide MPA 62307-3; 3: *Biconidinium longissimum*; Le Tillet core, 144.8 m depth; slide MPA 62331-4; 4: *Axiodinium lunare*; Cap d'Ailly cliff section, 35 m height; slide 61781; 5: *Stenodinium meckelfeldense*; Cap d'Ailly cliff section, 38 m height; slide 61788; 6: *Axiodinium lunare*; Cuise-la-Motte core, 82.5 m depth; slide 59969-2; 7: *Dracodinium astra-lobiscum*; Siège-Madame core, 8.9 m depth; slide MPA 62339-2; 10: *Biconidinium longissimum*; Sinceny core, 6.2 m depth; slide MPA 62290-7; 9: Gonyaulacoid B; Try core, 6.7 m depth; slide MPA 62339-2; 10: *Biconidinium longissimum*; Sinceny core, 6.2 m depth; slide MPA 59804-3; 11: *Glaphyrocysta* aff. *ordinata*; Siège-Madame core, 13.0 m depth; slide MPA 62304-2; 12: Gonyaulacoid B; Try core, 6.0 m depth; slide MPA 62335-3; 13: *Trigonopyxidia ginella*; Siège-Madame core, 13.0 m depth; slide MPA 62304-2; 14 and 17: Gonyaulacoid A; Vasterival section, 2 m height; slide MPA 59922-3; 15: *Melitasphaeridium pseudorecurvatum*; Siège-Madame core, 9.6 m depth; slide MPA 62299-6; 16: Gonyaulacoid A; Criel cliff section, 9.7 m height; slide MPA 59955-4; 19: Gonyaulacoid C; Siège-Madame core, 7.8 m depth; slide MPA 62298-4.

Calibration: the *Dracodinium astra* Zone corresponds indirectly to the mid part of the NP10 Zone interval.

Chronostratigraphic Age: Early Eocene (Early Ypresian s.s.) (~55.0–54.8 Ma).

It must be noted that the *Wetzeliella* (now *Dracodinium*) astra Zone was first established in the Paris Basin by Châteauneuf and Gruas-Cavagnetto (1978) in the lower part of the Sables de Laon Member between the LO of *Dracodinium* (=*Wetzeliella*) astra and LO of *Stenodinium* (=*Wetzeliella*) meckelfeldense. The present version of the *Dr. astra* Zone differs by the use of species Axiodinium (=*Wetzeliella*) lunare as a second (or sometimes only) marker for the upper zonal limit definition.

The *Dracodinium astra* Zone is known from different parts of the North Sea Basin: in southern England (Powell *et al.*, 1996) and in the central part of the North Sea (Balder Formation; AI, pers. data). It corresponds to the D6a Subzone of the German sector of the North Sea (Köthe, 2012). According to our unpublished data from the south of England, the *Dracodinium astra* Zone interval is also recognized within the lower London Clay Fm in the BGS London Jubilee Line 404T and Shamblehurst-Lane cores.

4.7 The Axiodinium Iunare/Stenodinium meckelfeldense Zone (Paris and Dieppe basins)

Definition: interval from the LOs of *Axiodinium lunare* and *Stenodinium meckelfeldense* to the LO of *Dracodinium simile*.

Diagnostic events: the species *Deflandrea phosphoritica*, *Sophismatia crassoramosa*, *Sophismatia tenuivirgula*, *Axiodinium prearticulatum*, *Heteraulacacysta everriculata* occur within this zone interval in the Paris and Dieppe basins.

Reference section in the Paris Basin: Mont-Notre-Dame Fm (Sables d'Aizy Member, 137.0–133.0 m depth), Le Tillet core, Oise Department (former Picardy, now Hauts-de-France Region).

This zone is also established within the Sables d'Aizy Member of the Mont-Notre-Dame Fm in the Therdonne and Cuise-la-Motte cores, within the Epernay Fm in the Venteuil core, within the Orchies Member in the Flines-lez-Râches outcrop section from the transitional area between the Paris and Belgian basins, and within the Flandres Fm in the Bois-de-Ville core in southern Belgium.

Reference section in the Dieppe Basin: Varengeville Fm (Argiles et Sablons Member, 5.5–3.0 m depth), Siège-Madame core, Seine-Maritime, Normandy.

In the Dieppe Basin this zone is also established in the Cap d'Ailly cliff section.

Calibration: the *Axiodinium lunare/Stenodinium meck-elfeldense* Zone corresponds to the upper part of the NP10 Zone interval.

Chronostratigraphic Age: Early Ypresian s.s. (~54.8–53.4 Ma).

The Wetzeliella meckelfeldensis Zone was originally established in northern France by Châteauneuf and Gruas-Cavagnetto (1978) in the lower Sables d'Aizy Member between the LO of Wetzeliella meckelfeldensis (now Stenodinium meckelfeldense) and the LO of Dracodinium simile. Based on our new dinocyst data from the Paris and Dieppe basins, we suggest the use of the LO of *Axiodinium lunare* (synchronous to the LO of *S. meckelfeldense*) as the second (or even often only) marker to define the lower zonal boundary.

The Stenodinium (=Wetzeliella) meckelfeldense Zone is known from different parts of the former North Sea Basin: in the Belgian Basin (De Coninck, 1991), in the central part of the North Sea (Balder Fm, AI, pers. data), in the lower London Clay Fm in southern England (Shamblehurst-Lane BGS core, unpublished). It corresponds to the D6a Subzone of the German part of the North Sea (Köthe, 2012) and to the E2a Subzone of the North Sea zonation of Bujak and Mudge (1994).

5 Discussion

5.1 The Paleocene interval and hiatuses

Thanetian sands are often considered as a unique glauconitic sandy unit in the Paris and Dieppe basins (see for example Rouvillois, 1960). It is not the place here to discuss extensively the twofold division of these so-called "Thanetian glauconitic sands", this will be done elsewhere arguing on lithological, sedimentological, paleontological and other criteria and new data. Nevertheless, it is necessary to put forwards evidence that supports such a two-fold division. The southwestern extension of the Paleogene strata north of the Seine valley provides such an opportunity as this region shows the maximum extent of these two transgressive sandy units, which crop out separately and have been paleontologically identified. The "Sable de Dieppe" Member that correlates with the Sables de Châlons-sur-Vesles Fm and belongs to the NP8 Zone rests directly on the Cretaceous chalk (Dupuis and Steurbaut, 1987). Near Beauvais, the well-known "Sable de Bracheux" that records the NP9a Zone, lies directly on the Cretaceous chalk without any sandy intercalation of NP8 age (Aubry, 1983). In addition, each sand unit can be easily equated with the two equivalent but distinct formations from southeast UK, the Thanet Fm and the Upnor Fm that are separated by a surface representing a major drop in sea level (Knox, 1996). The fine-grained unit that forms laterally the base of the sequence of the Dieppe - Châlons-sur-Vesles sands, is only present in the north and the east of the Paris Basin, it is not younger than the NP6-7 zones and it is distinct from the Selandian, which belongs only to the NP6 zone (Schmitz et al., 2011). Consequently, there is a significant hiatus between the Early Paleocene represented by the Vigny Group and the Upper Paleocene Vesles Group in the Paris Basin.

Our new data confirm the absence of any Selandian deposits in the Paris and Dieppe basins and no units dating from the lower part of the Early Thanetian (NP6 to NP7 Zones) has been obtained here either. Instead, the upper part of the Lower Thanetian and the Upper Thanetian (NP8 and NP9a) are revealed in a number of reference sections in northern France.

The major part of the Châlons-sur-Vesles Fm in the Paris Basin corresponds to the *Alisocysta margarita* Zone interval and clearly correlates with the Thanet Sand Fm in southern England, the Wizernes "Tuffeau" and Grandglise Sand members in the transitional zone between the Paris and Belgian basins. Such widespread distribution of the upper part of the Lower Thanetian deposits from the London to the Paris and Belgian basins indicates an important transgressive phase in the development of the North Sea Basin after one or a few long regressive episode(s) and/or hiatus(es) during the whole Selandian and locally also during the early part of the Early Thanetian.

The Upper Thanetian sediments of Bracheux and lowermost Mortemer formations contain the dinoflagellate cyst assemblage, corresponding to the *Apectodinium hyperacanthum* Zone interval and are generally characterized by up to 30% (and even up to 50% in the Dieppe Basin) of *Apectodinium* spp. Lithologically varied Upper Thanetian sediments are widely distributed over the Paris and Dieppe basins, in transitional zone between the Paris and Belgian basins (Vervins, Viesly Crag and Vertain Crag members of the Hainaut-Valenciennois Fm) and in southern England (Upnor Fm), suggesting a new significant transgression during the Late Thanetian in the North Sea Basin, as suggested by Steurbaut (1998) and Aubry *et al.* (2005), and as known in other regions of western Eurasia like eastern Peri-Tethys and West Siberia (Iakovleva and Aleksandrova, 2014) as well.

5.2 The PETM event

As was mentioned above, the onset of the CIE associated with the PETM event, starts within the Mortemer Fm, which was deposited in an almost entirely terrestrial environment and continues through the whole Soissonnais Fm (terrestrial and lagoonal depositional environments). The CIE interval in these littoral-lagoonal facies is characterized by an acme of *Apectodinium* spp. (70–98%). The Mortemer Fm, mostly accumulated in terrestrial depositional environments rich in carbonates, and as such rarely yielded dinoflagellate cyst assemblages that can be counted quantitatively. Nevertheless, our data from the Therdonne core and section show that the beginning of the *Apectodinium*-acme almost coincides with the CIE onset within the Mortemer Fm.

The Soissonnais Fm, also corresponding to the CIE event and composed of alternating clay, silt and lignite lithofacies including coquina beds or laminae, is characterized, in its lagoonal part, by dinocyst assemblages dominated by Apectodinium (70-98%). Nevertheless, it should be noted that while the Soissonnais Fm in the Paris Basin (cf. Sinceny core, etc.) is characterized exclusively by the Apectodiniumacme, in the Dieppe Basin (Cap d'Ailly cliff section and Phare d'Ailly and Siège-Madame cores) the same formation revealed in its lower half an alternation of the Apectodinium-acme (presumably heterotrophic dinoflagellates) and the acmes of autotrophic groups: Kenleyia, Lingulodinium and other gonyaulacoids of uncertain systematic affinity (Gonyaulacoids A, B, C; Plate 1, fig. 12; Plate 3, figs. 9, 12, 14, 16, 17) in the lowermost SAOM Member. This alternation of extreme acmes is supported by our data from the Woolwich Formation in southern England (from the London Jubilee Line 404T core, BGS collection), where we recognized not only the same Apectodinium-acme, but the acme (35%) of Gonyaulacoid A as well. This noticeable alternation of almost monospecific dinoflagellate cyst assemblages may indicate prominent changes in nutrient availability and may be explained by exceptionally specific environments during the so-called Sparnacian times in the Dieppe-Hampshire and London basins.

The upper part of the "Sparnacian" deposits (Craquelins Member in the Dieppe Basin; Vauxbuin Member in the Paris Basin) is characterized by a relative decrease in *Apectodinium* abundance and increase in *Spiniferites-* and *Areoligera-*groups as well as by the occurrence of a number of species of Wetzelielloideae (Iakovleva, 2017), suggesting a relative sealevel rise at the end of the PETM.

As mentioned by Gruas-Cavagnetto (1976c), dinoflagellate cyst assemblages from the Dieppe-Hampshire and Paris basins' "Sparnacian" do not contain the key-species Axiodinium (=Apectodinium) augustum (nominate species of the A. augustum Zone mostly corresponding to the PETM interval worldwide). It is also the case at Schöningen in Germany (Methner et al., 2019), whereas it is present in northern Belgian Tienen Formation and is coeval there with the CIE and Apectodinium-acme interval (Steurbaut et al., 2003). As previously noted, Powell et al. (1996) explained the absence of Axiodinium augustum in the Anglo-Paris Basin by its restriction to more offshore conditions. According to our new data from northern France, the species Axiodinium augustum is virtually absent from the Laon outcrop section, although a few specimens were seen in unfavourable orientations on the microscope slide which might be identified as this species. However, instead of Axiodinium augustum a significant number of specimens of Apectodinium parvum, which are longer both in overall length and in the length of the apical and antapical horns (compared to the holotype) were observed here (Plate 1, fig. 1). We presume that this atypical morphotype of Apectodinium parvum could represent an ecological onshore substitute of Axiodinium augustum. Additionally, the uppermost part of the PETM interval within the "Sparnacian" deposits (Craquelins Member in Dieppe Basin, Vauxbuin Member in Paris Basin) is characterized by the appearance of several wetzelielloidean species: Axiodinium sparnacium, Epelidinium brinkhuisii, Epelidinium normandiense, Petalodinium lenisium, Stichodinium elegantulum, Stichodinium galliciense, Stichodinium sympagicum, Stichodinium prostimus, Vallodinium heilmannii, Vallodinium picardicum, and Wilsonidium modicum.

5.3 The Early Eocene record, postdating the PETM

Until now, it was considered that there was no evidence for dinocyst assemblages assignable to the *Glaphyrocysta* ordinata or its equivalent Deflandrea oebisfeldensis Zone in the Paris and Dieppe basins (Aubry et al., 2005): there was no northern France record of the Leiosphaeridia-acme, D. oebisfeldensis-abundance or Glaphyrocysta/Areoligeradominance documented from the Harwich Fm in southern England (Powell et al., 1996) and in the North Sea (Mudge and Bujak, 1996). Based on our new data it appears that the lowermost unit (postdating the PETM) of the Mont-Notre-Dame Fm in the Paris Basin (Sinceny Member, introduced by Quesnel et al., 2011) corresponds to a littoral depositional environment, with homogeneous $\delta^{13}C_{or}$ values between -24-25% PDB and contains a distinctive dinoflagellate cyst assemblage, characterized by the Biconidinium longissimum-acme combined at its base with still abundant Apectodinium spp. (up to 50%). The Biconidinium longissimum-acme event is unknown from the adjacent Belgian, Hampshire and London basins and possibly reflects a local and extremely specific environment during this time in the Paris Basin (with specific nutrient availability and reduced salinity). We suggest that the interval of the new Biconidinium longissimum-acme Zone corresponds to the lowermost Ypresian Glaphyrocysta ordinata/or Deflandrea oebisfeldensis Zone, indicating a more continuous sedimentation during the Early Eocene in the Paris Basin and, then, the absence or much less importance of the stratigraphical hiatus previously hypothesized by Aubry et al. (2005). It may be noted that, according to our data, in southern England the dinoflagellate cyst assemblages of the Glaphyrocysta ordinata/Deflandrea oebisfeldensis Zone recognized within the Harwich Fm in different localities often have significant differences even within short distances. Indeed the dinoflagellate cyst assemblages from the lower Harwich Fm (Orwell Unit) may be characterized by poor associations dominated by Spiniferites-, Lingulodinium-groups and Apectodinium spp. (Hole Farm Quarry, BGS core 81/46A) or, alternatively, by a Palaeotetradinium minusculum-acme (60%, BGS Shotley Gate core). The upper Harwich Fm (Wrabness Unit), in its turn, is either characterized by depleted dinocyst associations containing up to 15% of Deflandrea oebisfeldensis (BGS Shotley Gate core) or by those with a Deflandrea oebisfeldensis-acme (70-40%, Hole Farm Quarry).

When comparing the Paris and Dieppe basin successions, it can be noted that in the sections from the Pays de Caux and Vimeu (Cap d'Ailly cliff section, Siège-Madame core) the lowermost part of the Varengeville Fm is represented by the "Sables Fauves" Member (Dupuis and Steurbaut, 1987). The lower part of the "Sables Fauves" appears to be an unfavorable facies for palynomorph preservation and does not contain any dinoflagellate cyst in the Cap d'Ailly section or the Phare d'Ailly core. Nevertheless, it is possible that the "Sables Fauves" Member is stratigraphically equivalent to the Sinceny Member in the Paris Basin, the Zoute Silt Member in Belgium (data from De Coninck in Steurbaut, 1998) and the Harwich Fm including the Oldhaven Sand Member in southern England, at least below the LO of *Dracodinium astra*.

Overlying the Sinceny Member in the Paris Basin and the Sables Fauves Member in the Dieppe Basin respectively, the Sables de Laon Member (Mont-Notre-Dame Fm), the Argiles et Sablons Member (Varengeville Fm) as well as the lowermost London Clay Fm in the London Basin and the Mont-Héribu Clay in the Belgian Basin are characterized by the LOs of *Dracodinium astra* and *Dracodinium lobiscum*, indicating their Early Ypresian s.s. age. The next units of these formations contain, sequentially, the LOs of the younger key-species *Axiodinium lunare*, *Stenodinium meckelfeldense*, *Sophismatia crassoramosa*, *Sophismatia tenuivirgula*, *Dracodinium simile*, *Dracodinium varielon-gitudum* and *Charlesdowniea coleothrypta*.

6 Conclusions

Thanks to a new high-resolution palynological study, an updated version of the Late Paleocene-Early Eocene dinoflagellate cyst zonation for the Paris and Dieppe basins is proposed and contains six new or revised zones: *Alisocysta margarita*, *Apectodinium hyperacanthum*, *Apectodinium*-acme, *Biconidinium longissimum*-acme, *Dracodinium astra*, Axiodinium lunare/Stenodinium meckelfeldense. Based on combined bio-, litho- and chemostratigraphic data, the peculiarities of dinoflagellate cyst assemblages from the socalled "Sparnacian" deposits in northern France have been recognized: thus, the dinoflagellate cyst assemblages corresponding to the PETM event interval are characterized by an acme of Apectodinium spp., sometimes alternating with an acme of few gonyaulacoid groups in the Dieppe Basin. Dinoflagellate cyst assemblages from the PETM interval contain a significant number of atypical, longer specimens of Apectodinium parvum, which could represent an ecological onshore equivalent of species Axiodinium augustum in the Paris and Dieppe-Hampshire basins. The establishment of a new Biconidinium longissimum-acme Zone suggests that the stratigraphic hiatus (\sim 55.6–55.0 Ma) previously inferred in the Paris Basin, does not exist.

Supplementary Material

Supplement 1. Raw palynological data from the studied sections considered in the present work. Raw data are the property of the BRGM and cannot be used without a special permission of the authors and the BRGM.

Supplement 2. List of locations of the studied sections.

The Supplementary Material is available at https://www.bsgf. fr/10.1051/bsgf/2021035/olm.

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Appendix. List of dinoflagellate cyst species

Alisocysta margarita Harland, 1979

Alisocysta sp. 2 sensu Heilmann-Clausen, 1985

Apectodinium folliculum Islam, 1983

Apectodinium homomorphum (Deflandre and Cookson, 1955) Lentin and Williams, 1977

Apectodinium hyperacanthum (Cookson and Eisenack, 1965) Lentin and Williams, 1977

Apectodinium paniculatum (Costa and Downie, 1976) Lentin and Williams, 1977

Apectodinium parvum (Alberti, 1961) Lentin and Williams, 1977

Apectodinium quinquelatum (Williams and Downie, 1966) Costa and Downie, 1979

Apectodinium summissum (Harland, 1979) Lentin and Williams 1981	Hystrichosphaeridium tubiferum (Ehrenberg, 1838) Davey
Analizana cononata (Watzal 1022) Lajanna Corportion 1028	Ally Williams, 1975 Molitographic and an and an angle of the Margan and the 1066)
Areoligera ginningansis Iollay 1002	Ruiok at al 1080
Areoligeru gippingensis Joney, 1992	Dujak et ul., 1980 Palacomstodinium lidiae (Corko, 1063) Dovov 1060
Areoligera medusettijormis (weizel, 1955) Lejeune-Carpeni-	1 ulueocyslouinium liulue (Golka, 1905) Davey, 1909
Anglia and a subscript Laisana Companyian 1028	Palaeotetradinium minusculum (Alberti, 1961) Stover and
Areoligera senonensis Lejeune-Carpentier, 1938	Evitt, 1978
Axioainium iunare (Gocni, 1969) williams et al., 2015	Petalodinium lenisium Iakovleva, 2016
Axioainium prearticulatum Fensome et al., 2009	Phthanoperidinium crenulatum (De Coninck, 1975) Lentin
Axioainium sparnacium lakovieva, 2016	and Williams, 1977
Biconidinium longissimum Islam, 1983	Sophismatia crassoramosa (Williams and Downie, 1966)
Cleistosphaeridium polypetellum (Davey et al., 1966) Islam,	Williams et al., 2015
	Sophismatia tenuivirgula (Williams and Downie, 1966b)
Conneximura fimbriata (Morgenroth, 1968) May, 1980	Williams et al., 2015
Deflandrea denticulata Alberti, 1959	Stenodinium meckelfeldense (Gocht, 1969) Williams et al.,
Deflandrea phosphoritica Eisenack, 1938	2015
Dracodinium astra (Costa et al., 1978) Williams et al., 2015	Stichodinium elegantulum Iakovleva, 2016
Dracodinium lobiscum (Williams and Downie, 1966) Wil-	Stichodinium galliciense Iakovleva, 2016
liams <i>et al.</i> , 2015	Stichodinium parisiense Iakovleva, 2016
Dracodinium? modestum Iakovleva, 2016	Stichodinium prostimus Iakovleva, 2016
Epelidinium brinkhuisii Iakovleva, 2016	Stichodinium sympagicum Iakovleva, 2016
Epelidinium normandiense Iakovleva, 2016	Tanyosphaeridium xanthiopyxides (Wetzel, 1933) Stover and
Glaphyrocysta divaricata (Williams and Downie, 1966)	Evitt, 1978
Stover and Evitt, 1978	Trigonopyxidia ginella (Cookson and Eisenack, 1960) Downie
Glaphyrocysta pastielsii (Deflandre and Cookson, 1955)	and Sarjeant, 1965
Stover and Evitt, 1978	Vallodinium heilmannii Iakovleva, 2016
Heteraulacacysta everriculata Islam, 1983	Vallodinium picardicum Iakovleva, 2016
Homotryblium tasmaniense Cookson and Eisenack, 1967	Vallodinium sp. A sensu Iakovleva, 2016
Homotryblium tenuispinosum Davey and Williams, 1966	Wilsonidium modicum Iakovleva, 2016

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