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General palaeontology (Biostratigraphy)

A new terrestrial vertebrate site just after the Paleocene–Eocene boundary in the Mortemer Formation of Upper Normandy, France

Un nouveau site à vertébrés terrestres juste après la limite Paléocène–Eocène, dans la Formation de Mortemer en Haute-Normandie, France

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ABSTRACT

European terrestrial vertebrate sites of the Upper Paleocene–Lower Eocene deposits are predominantly known from the central and eastern parts of the Paris Basin. However, several outcrops covering this interval are scattered along the Upper Normandy coast, in the western part of the Paris Basin. Here we report the discovery of a new terrestrial vertebrate site in the Mortemer Formation, at the top of the cliffs of Sotteville-sur-Mer in Upper Normandy, France. The vertebrate level is situated about 1.5 m above the onset of the Paleocene–Eocene Carbon Isotope Excursion (CIE) based on dispersed organic carbon and is therefore Earliest Eocene in age. The vertebrate fauna is composed of fish, amphibians, lizards and mammals, including the earliest peradectid marsupials and paromomyid plesiadapiform of Europe. A diverse and rich charophyte flora is well represented throughout the lower part of the outcrop and allows the conclusion that the CIE falls in the *Peckichara disermas* biozone.

RÉSUMÉ

La plupart des sites à vertébrés terrestres du Paléocène supérieur–Eocène inférieur d'Europe sont connus du Centre et de l'Est du Bassin de Paris. Cependant, plusieurs affleurements de cet intervalle de temps sont éparpillés le long de la côte en Haute-Normandie dans l'Ouest du Bassin de Paris. Dans cet article, nous faisons état de la découverte d'un nouveau site à vertébrés terrestres dans la Formation de Mortemer, au sommet des falaises de Sotteville-sur-Mer en Haute-Normandie, France. Le niveau à vertébrés est situé

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environ 1,5 m au-dessus du point initial de l'Excursion Isotopique du Carbone de la limite Paléocène–Eocène (CIE), mise en évidence à partir du carbone organique dispersé. Il est donc daté de l'Eocène basal. La faune de vertébrés comprend des poissons, des amphibiens, des lézards et des mammifères dont les plus anciens marsupiaux peradectidés et le plus ancien plésiadapiforme paromomyidé d'Europe. Une flore riche et variée de charophytes, bien distribuée le long de la partie inférieure de l'affleurement permet de préciser que la CIE est située dans la biozone à *Peckichara disermas*.

1. Introduction

In the course of integrative studies of the Paleocene–Eocene transition in the Paris Basin, conducted by the *Bureau de recherches géologiques et minières* ([BRGM] – French Geological Survey), new explorations have been performed in Paleocene/Eocene (P/E) outcrops scattered along the Upper Normandy coast. These well-exposed sections are continuously renewed by erosion and are located in a central position in the sub-basins of the southern North Sea Basin. Therefore they can be considered as reference sections for the NW European continental-shallow marine P/E deposits. The P/E boundary coincides with a rapid and high-amplitude global warming called the Paleocene–Eocene Thermal Maximum (PETM) associated with a negative Carbon Isotope Excursion (CIE). This event is especially relevant as it is characterized by the appearance and rapid dispersal of earliest modern mammal orders in the Northern Hemisphere (Smith et al., 2006). Here we report the discovery of a new terrestrial vertebrate site just above the CIE recorded in the same section at the top of the cliffs of Sotteville-sur-Mer in Upper Normandy (Fig. 1).

2. Geological setting

The section of Sotteville-sur-Mer is located about 650 m north of the center of Sotteville-sur-Mer village, and about 150 m east of the main stairs that lead to the beach. The locality is also known under the local name 'La Pointue'. This section has been described several times since 1894 (Gruas and Bignot, 1985) and the coordinates

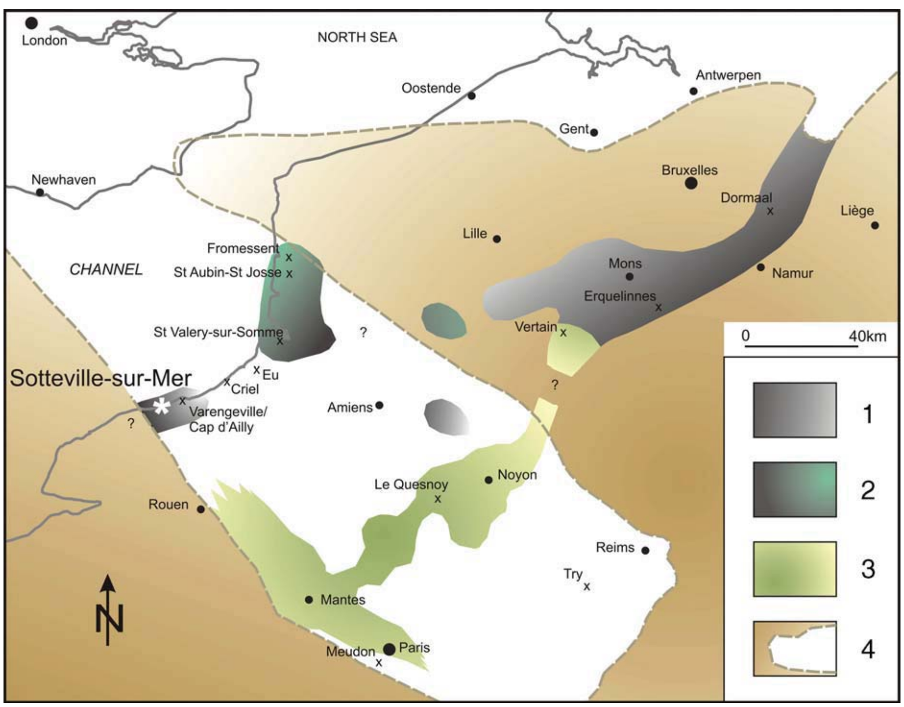


Fig. 1. Location of the Sotteville-sur-Mer section on the western side of the Paris Basin. The paleogeographic sketch shows the main Uppermost Paleocene–Lowermost Eocene continental localities of the southern North Sea Basin. Scattered outliers: 1. Lignite deposits; 2. Silty deposits with *Unio* and *Polymesoda cordata* bivalves; 3. Carbonate rich deposits (calcretes, lacustrine limestones...); 4. Attempted reconstruction of the extension of the Earliest Eocene lagoonal deposits (Soissonnais Formation).

Fig. 1. Localisation de la coupe de Sotteville-sur-Mer sur le bord ouest du Bassin de Paris. Le schéma paléogéographique indique les principales localités continentales du Paléocène terminal–Eocène basal du Sud du Bassin de la Mer du Nord. Buttes témoins éparpillées : 1. Dépôts de lignite ; 2. Dépôts silteux à bivalves *Unio* et *Polymesoda cordata* ; 3. Dépôts riches en carbonates (calcrètes, calcaires lacustres...) ; 4. Essai de reconstruction de l'extension des dépôts lagunaires de l'Eocène basal (Formation du Soissonnais).

Fig. 2. 1: View of the Sotteville-sur-Mer cliff. The Upper Paleocene–Lower Eocene deposits of the Mont-Bernon Group are extended on about 7 m at the top of the cliff and overly about 35 m of Campanian chalk. Location of the base of the Mont-Bernon Group is indicated by an arrow. 2: Top of the cliff with the vertebrate site situated about 2.5 m above the base of the Mont-Bernon Group (indicated by an arrow). 3: Top of the cliff with the Pays-de-Caux Member and the lower part of the Calcaire d'Ailly Member overlying the Campanian chalk. Orange sands of the Sotteville-sur-Mer Member are visible at the top. 4: The Calcaire d'Ailly Member with the three visible units. 5: Digging of the unit 2 and 3 of the Calcaire d'Ailly Member with the underlying unit 1 and top of the Pays-de-Caux Member in the background. 6: Digging of the unit 2 and 3 of the Calcaire d'Ailly Member with the overlying Sotteville-sur-Mer Member and the Craquelins Member in the background. 7: Part of the Calcaire d'Ailly Member with top of unit 2 (yellow clay at 2.47, light grey marly layer with vertebrate remains at 2.55, lignite at 2.70) and base of unit 3 (grey-blue clay). 8: Upper part of the Sotteville-sur-Mer Member.

Fig. 2. 1 : Vue de la falaise de Sotteville-sur-Mer. Les dépôts du Paléocène supérieur–Eocène inférieur du Groupe du Mont-Bernon s'étendent sur environ 7 m au sommet de la falaise et surmontent environ 35 m de craie du Campanien. La localisation de la base du Groupe du Mont-Bernon est indiquée par une flèche. 2 : Sommet de la falaise avec le site à vertébrés situé à 2,5 m au-dessus de la base du Groupe du Mont-Bernon (indiqué par une flèche). 3 : Sommet de la falaise montrant le Membre du Pays-de-Caux et la partie inférieure du Membre du Calcaire d'Ailly surmontant la craie du Campanien. Les sables orange du Membre de Sotteville-sur-Mer sont visibles au sommet. 4 : Le Membre du Calcaire d'Ailly avec les trois unités visibles. 5 : Dégagement des unités 2 et 3 du Membre du Calcaire d'Ailly avec l'unité 1 sous-jacente et le sommet du Membre du Pays-de-Caux en arrière plan. 6 : Dégagement des unités 2 et 3 du Membre du Calcaire d'Ailly avec le Membre de Sotteville-sur-Mer sus-jacent et le Membre des Craquelins en arrière-plan. 7 : Partie du Membre du Calcaire d'Ailly avec le sommet de l'unité 2 (argile jaune à 2,47, couche marneuse gris clair avec les restes de vertébrés à 2,55, lignite à 2,70) et la base de l'unité 3 (argile gris-bleu). 8 : Partie supérieure du Membre de Sotteville-sur-Mer.

of the vertebrate site are 49°53'18.19"N, 0°49'51.73"E. The Paleocene–Eocene deposits that belong to the Mont-Bernon Group are more than 7 m thick and overly the Upper Cretaceous chalk (Fig. 2). From the base to the top of the measured section, four main members are delineated: the Pays-de-Caux Member (PDC Mb), the Calcaire d'Ailly Member (CA Mb), the Sotteville-sur-Mer Member (new name) (SM Mb) and the Craquelins Member (CR Mb). The PDC Mb and CA Mb belong to the carbonate-rich continental Mortemer Formation, and the SM Mb and CR Mb belong to the

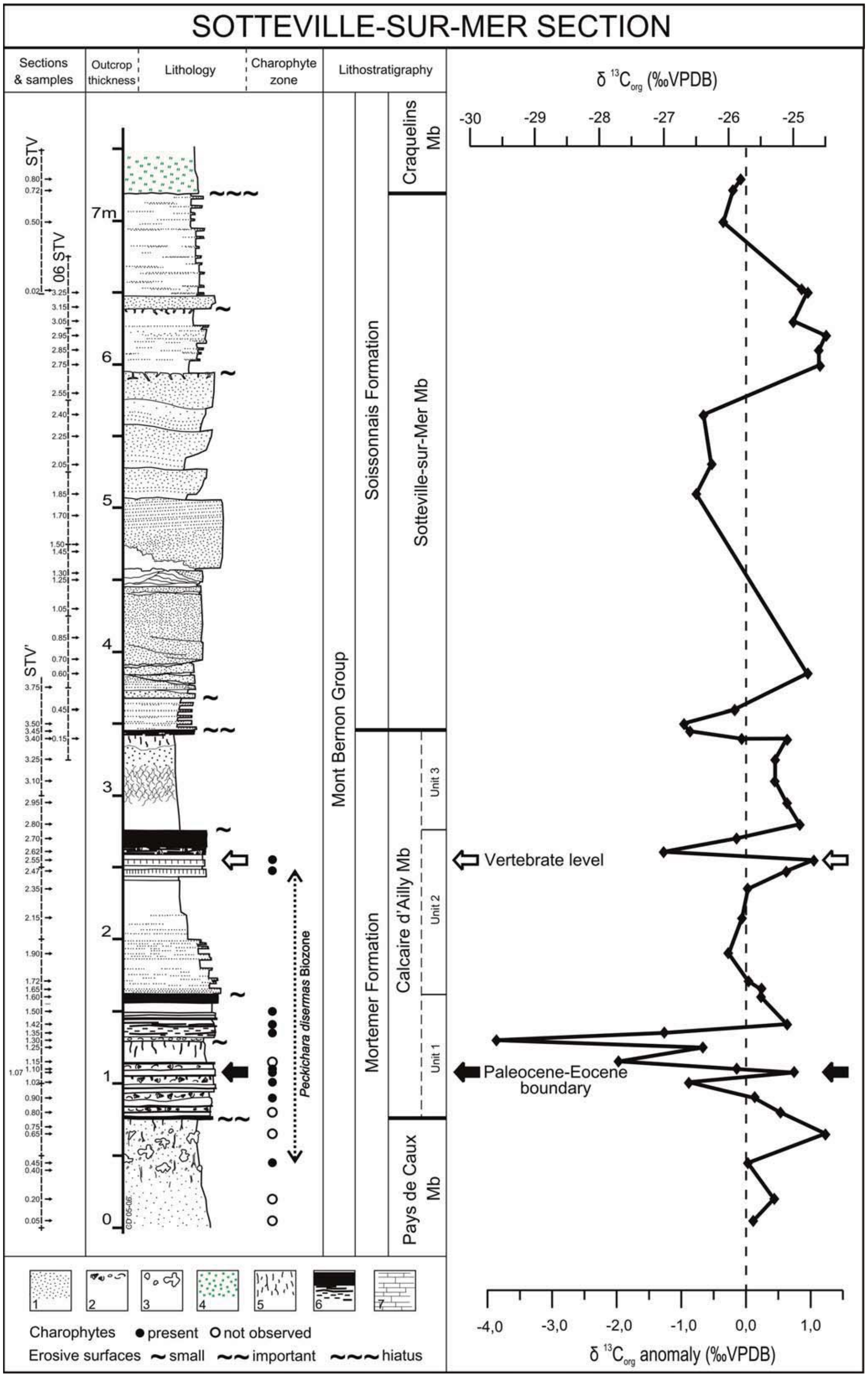

SOTTEVILLE-SUR-MER SECTION
Sections & samples
Outcrop thickness
Lithology
Charophyte zone
Lithostratigraphy
δ 13Corg (‰VPDB)
Craquelins Mb
Sotteville-sur-Mer Mb
Soissonnais Formation
Mont Bernon Group
Calcaire d'Ailly Mb
Mortemer Formation
Pays de Caux Mb
Unit 1
Unit 2
Unit 3
Peckichara disermas Biozone
Vertebrate level
Paleocene-Eocene boundary
Charophytes ● present ○ not observed
Erosive surfaces ~ small ~~ important ~~~ hiatus
δ 13Corg anomaly (‰VPDB)

Fig. 3.

Soissonnais Formation following the new lithostratigraphical classification of the "Sparnacian" in the Paris Basin (Aubry et al., 2005).

Except for the SM Mb, all the members may be referred to the nearby Cap d'Ailly section (Bignot, 1965; Dupuis and Steurbaut, 1987; Dupuis and Thiry, 1998; Magioncalda, 2004). The top of the PDC Mb in which the studied section begins is a calcareous sand with local lacustrine limestone lenses and quartzite silcrete concretions that are difficult to see *in situ*. The CA Mb has a sharp and rooted surface with the underlying PDC Mb, and is composed of 3 units. The lower one, unit 1, contains two sets of thinly bedded lacustrine limestones rich in freshwater mollusks (80–90% of carbonate) separated by a more clayey layer (about 5% carbonate). Thin lignite beds are regularly interstratified and one of them caps the unit. We consider unit 1 a lateral equivalent of Lignite 1 of the CA Mb of the Cap d'Ailly section. Unit 2 begins with a rather thick grey clay, the lower part of which is sandy and thinly stratified. Thin lacustrine layers with a lesser carbonate content (about 5–10%) and a lignite cap mark the top of unit 2. The vertebrate layer corresponds to these thin lacustrine layers. Unit 3 is made of distinctive bluish clay covered by a thin lignite layer resting on a rooted surface.

The newly named Sotteville-sur-Mer Member is formed by several sandy units sandwiched between clayey units at the base and at the top. At the base, the pale blue grey clay is laminated by silt layers and highly bioturbated. At the top, the blue grey clayey layers become gradually less sandy. The sands, yellowish or light brown in color, show stratifications of probable tidal origin. This Member is correlative to the brackish/lagoonal Ailly Mb of the Cap d'Ailly section. However, the lithology of the Ailly Mb differs by the alternation of centimeter-thick layers of coquina, clays and silts. The sandy intercalations are less important than in the SM Mb. Moreover, the Ailly Member is divided into two parts by a paleosol with a lignite horizon overlying a variegated clay with root traces. At the top of the section, only the very base of the CR Mb crops out currently. It is a pinkish brown clay rich in pale green glauconite.

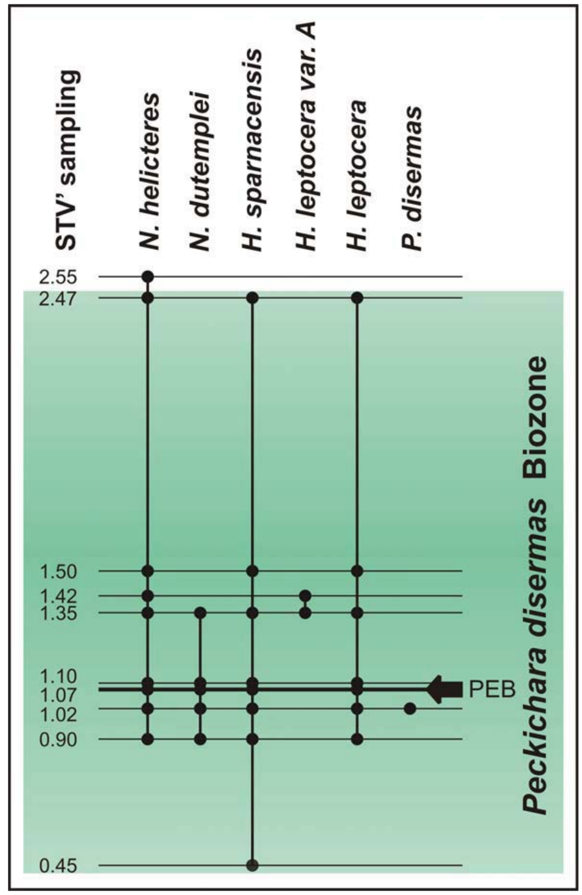


Fig. 4. Diversity and distribution of the charophytes from the Mortemer Formation of the Sotteville-sur-Mer section. PEB: Paleocene–Eocene boundary.

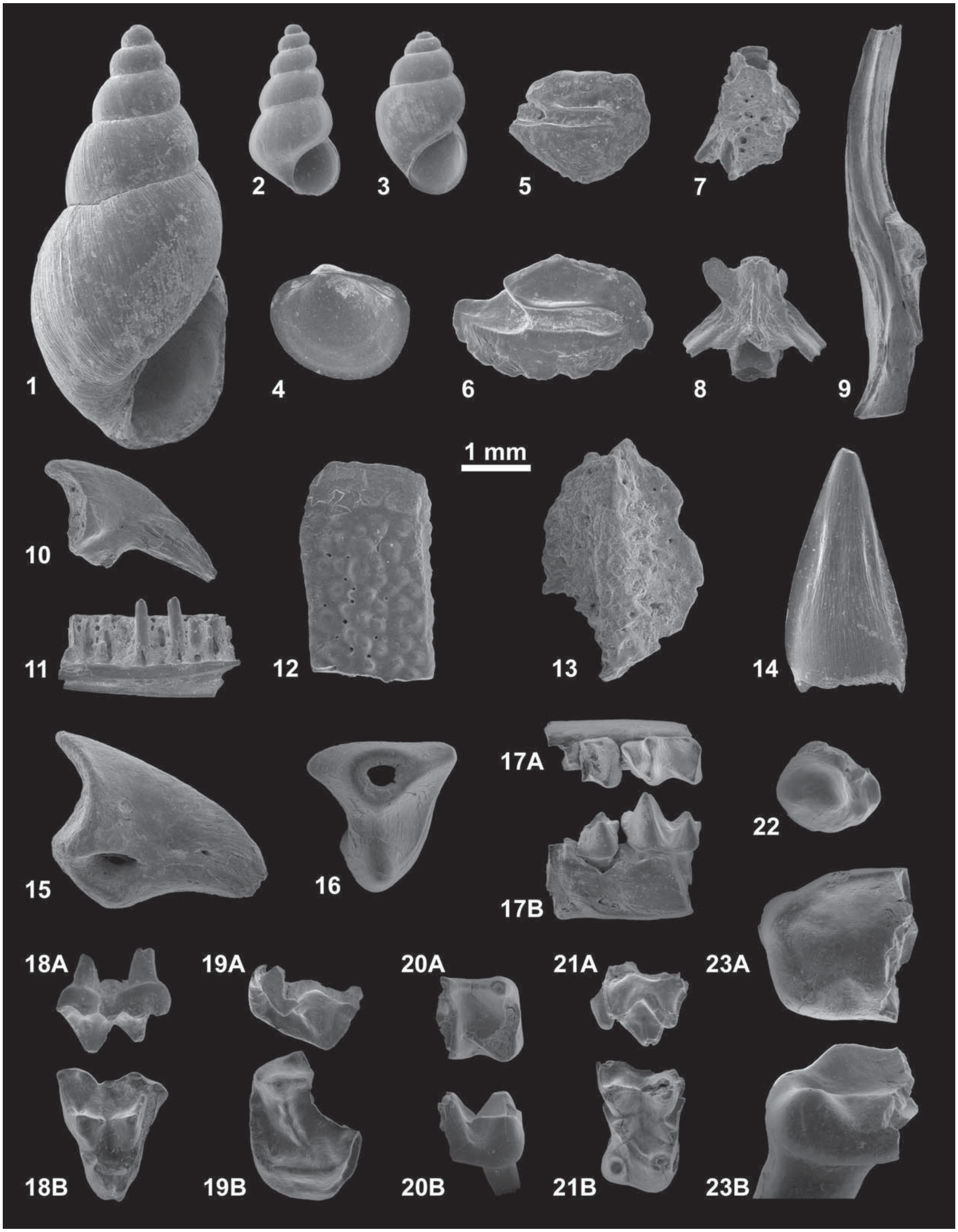
Fig. 4. Diversité et distribution des charophytes dans la Formation de Mortemer de la coupe de Sotteville-sur-Mer. PEB : limite Paléocène–Eocène.

3. Methods

The carbon-isotope ratios of bulk organic matter (Dispersed Organic Carbon [DOC]) were measured on 45 samples spanning 7.25 m of the succession (average of one sample per ~0.15 m, see complete methodology in Magioncalda et al., 2004; Schnyder et al., 2009; Yans et al., 2006, 2010). Bulk sediment samples of about 40 g each were first dried and then cleaned, removing surface oxidation to exclude potential sources of degraded organic matter. Samples were then powdered and treated with HCl 25% for at least 1 hour to remove carbonates. Soluble salts were removed by repetitive centrifuging (4000 revolutions per minute) until the neutral solution was obtained. Free carbonate samples were treated similarly. Finally the residue was dried at 35 °C and powdered again. Fractions of each resulting powder were measured with a standard LECO carbon analyzer (CS-200) to determine total organic carbon (TOC). Quantities required for analysis (between 0.07 and 25.1 mg) were calculated on the basis of the TOC values. Each sample was weighed into tin capsules and rolled into balls for continuous flow combustion and isotopic analysis using a Carlo Erba EA1110 elemental analyser coupled to a mass spectrometer (ThermoFinnigan

Fig. 3. Lithostratigraphy and carbon isotopes on dispersed organic carbon of the Sotteville-sur-Mer section. The vertebrate level, represented by an arrow, is situated 1.5 m above the onset of the CIE. Compositional variations between heavy clay and sand are suggested by the width of the column. Distinctive lithologies are however illustrated in the captions as follow: 1: sands; 2: shells; 3: carbonated concretions; 4: glauconite; 5: rootlets; 6: lignite and lignitic clay beds; 7: limestone.

Fig. 3. Lithostratigraphie et isotopes du carbone organique dispersé de la coupe de Sotteville-sur-Mer. Le niveau à vertébrés, représenté par une flèche, est situé 1,5 m au-dessus du point de départ de la CIE. Les variations de composition entre l'argile lourde et le sable sont suggérées par la largeur de la colonne. Les lithologies distinctes sont cependant illustrées dans les légendes comme suit : 1 : sables ; 2 : coquilles ; 3 : concrétions carbonatées ; 4 : glauconie ; 5 : racines ; 6 : lignite et lits d'argile ligniteuse ; 7 : calcaire.


1
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4
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1 mm
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13
14
15
16
17A
17B
22
18A
19A
20A
21A
23A
18B
19B
20B
21B
23B

Fig. 5.

delta plus XP). The analyses were performed combusting the sample at 1025 °C. Measured isotopic compositions were calibrated with the inter-laboratory international standards: sucrose IAEA-CH-6, oil NBS-22 and graphite USGS-24. TOC contents were checked by comparing to a laboratory standard (urea). Both standards (0.025 to 0.2 mg respectively in a purified tin cup) were measured repeatedly between each set of twenty samples. Organic ^{13}C values are reported as a proportion of ^{12}C in $\delta^{13}C$ notation normalized to the international PDB standard (VPDB, Vienna Peedee belemnite). Two distinct measurements were made for almost all samples. The overall precision of analyses is within 0.2‰ (1σ).

The paleontological content was analyzed in detail for the lower part of the section comprising the Pays-de-Caux Member and the Calcaire d'Ailly Member. Microfossils were obtained by fine screenwashing at 200 μm. Vertebrate remains were picked out and sorted under a binocular microscope after screenwashing sediments in laboratory through meshes of 5 mm, 2 mm and 1 mm. Pictures of the specimens were made with an Environmental Scanning Electronic Microscope FEI Quanta 200.

4. Results and discussion

4.1. Carbon isotope

In the whole Sotteville-sur-Mer succession (Fig. 3), the $\delta^{13}C_{DOC}$ values range from −24.5‰ to −29.6‰, in agreement with previous studies dealing with the dispersed organic matter at the Paleocene–Eocene boundary (Magioncalda et al., 2001, 2004; Smith et al., 2006; Steurbaut et al., 2003; Yans et al., 2006). From the base to the top of the succession we observe:

- quite stable $\delta^{13}C_{DOC}$ values from −25.6‰ at STV'0.05 to −25.0‰ at STV'1.07, with a potential negative peak at sample STV'1.02 (only one sample, $\delta^{13}C_{DOC}$ of −26.6‰);
- a negative-positive excursion, from $\delta^{13}C_{DOC}$ of −25.0‰ (sample STV'1.07) to minimal $\delta^{13}C_{DOC}$ of −29.6‰ (sample STV'1.30) – negative shift of 4.6‰, and recovery to $\delta^{13}C_{DOC}$ of −25.1‰ (sample STV'1.42) in the clayey part of the unit 1;
- quite stable $\delta^{13}C_{DOC}$ values from −25.1‰ at sample STV'1.42 to −24.8‰ at sample 06STV3.25, with potential negative peaks at STV'2.62 ($\delta^{13}C_{DOC}$ of −26.9‰), STV'3.45-STV'3.50 ($\delta^{13}C_{DOC}$ of −26.6‰ and −26.7‰) and 06STV1.85-06STV2.05-06STV2.4 ($\delta^{13}C_{DOC}$ of −26.5‰ to −26.4‰).

In the composite Cap d'Ailly section, Sinha (1997) showed a negative carbon isotope excursion (CIE from −26‰ to −27.5‰) on dispersed organic matter at the base of a lignite bed possibly belonging to the base of the complete lignite complex. Magioncalda et al. (2001) confirmed this excursion for samples at the same place but highlighted a second upper and high-amplitude negative excursion (from −25.3‰ to −29.7‰) at the top of the complete lignite complex. This high-amplitude excursion is similar in the Sotteville-sur-Mer and Cap d'Ailly sections and is here considered as the lower part of the CIE, marking at its onset the Paleocene–Eocene boundary.

4.2. Palaeontology

4.2.1. Charophytes

Oogones of charophytes (gyrogonites) are distributed from 0.45 m to 2.55 m. Three genera (*Nitellopsis, Harrisichara, Peckichara*) and six species of charophytes are recognized (Fig. 4). Among them, *P. disermas* and *H. Leptocera,* which are biostratigraphic markers of the *Peckichara disermas* biozone (Riveline et al., 1996), are present. *H. sparnacensis* is even present from 0.45 m to 2.47 m. Unit 1 of the Calcaire d'Ailly Member, which corresponds to the beginning of the CIE, shows the highest quantity and diversity of charophytes. The vertebrate level at 2.55 m presents a large number of charophytes but only of the species *Nitellopsis helicteres*.

4.2.2. Invertebrates

Several species of mollusks are present from 0.45 m to 2.55 m. Among them, shells of the gastropods *Hydrobia* sp. (Fig. 5 .1) and *Bithinella* sp. (Fig. 5.2–3) are numerous. The sphaeriid bivalve cf. *Sphaerium* sp. is also present (Fig. 5.4). The malacofauna is typical of fresh water and the genus *Bithinella* has been identified in unit 9 of the

Fig. 5. 1. Gastropod *Hydrobia* sp.; **2–3**. Gastropod *Bithinella* sp.; **4**. Bivalve cf. *Sphaerium* sp.; **5**. Otolith of salmoniform Osmeridae *Thaumaturus* sp.; **6**. Otolith of percoid *Anthracoperca* sp.; **7**. Vertebra with dermal plate of cf. *Notophtalmus* sp. in dorsal view; **8**. Vertebra of cf. *Salamandra* sp. in dorsal view; **9**. Surangular of frog in dorsal view; **10**. Claw of lizard in lateral view; **11**. Dentary fragment of scincomorph lizard in lingual view; **12**. Quadrate osteoderm of scincomorph lizard in dorsal view; **13**. Ovale osteoderm of varanoid necrosaurid lizard in dorsal view; **14**. Crocodilian tooth in lingual view; **15**. Claw of mammal in lateral view; **16**. Premolariform P4 of unidentified mammal in occlusal view; **17**. Left dentary fragment with m3 and talonid of m2 of marsupial *Peradectes* sp. 1 in occlusal (**17A**) and labial (**17B**) views; **18**. Right M2 or M3 of *Peradectes* sp. 2 in labial (**18A**) and occlusal (**18B**) views; **19**. Right M1 or M2 of paromomyid *Arcius* sp. in labial (**19A)** and occlusal (**19B**) views; **20**. Left m1 or m2 talonid of amphilemurid erinaceomorph *Macrocranion vandebroeki* in occlusal (**20A**) and labial (**20B**) views; **21**. Right M2 of *Macrocranion vandebroeki* in occlusal (**21A**) and labial (**21B**) views; **22**. P3 of rodent in occlusal view; **23**. Right m3 talonid of Ischyromyid rodent in occlusal (**23A**) and labial (**23B**) views.

Fig. 5. 1. Gastéropode *Hydrobia* sp. ; **2–3**. Gastéropode *Bithinella* sp. ; **4**. Bivalve cf. *Sphaerium* sp. ; **5**. Otolithe du salmoniforme Osmeridae *Thaumaturus* sp. ; **6**. Otolithe du percoïde *Anthracoperca* sp. ; **7**. Vertèbre à plaque dermique de cf. *Notophtalmus* sp. en vue dorsale ; **8**. Vertèbre de cf. *Salamandra* sp. en vue dorsale ; **9**. Surangulaire de grenouille en vue dorsale ; **10.** Griffe de lézard en vue latérale ; **11**. Fragment de dentaire de lézard scincomorphe en vue linguale ; **12**. Ostéoderme rectangulaire de lézard scincomophe en vue dorsale ; **13**. Ostéoderme ovale de lézard varanoïde necrosauridé en vue dorsale ; **14.** Dent de crocodile en vue linguale ; **15**. Griffe de mammifère en vue latérale ; **16**. P4 prémolariforme d'un mammifère indét. en vue occlusale ; **17**. Fragment de dentaire gauche avec m3 et talonide de m2 du marsupial *Peradectes* sp. 1 en vues occlusale (**17A**) et labiale (**17B**) ; **18**. M2 ou M3 droite de *Peradectes* sp. 2 en vues labiale (**18A**) et occlusale (**18B**) ; **19**. M1 ou M2 droite du paromomyidé *Arcius* sp. en vues labiale (**19A**) et occlusale (**19B**) ; **20**. Talonide d'une m1 ou m2 gauche de l'amphilémuridé érinacéomorphe *Macrocranion vandebroeki* en vues occlusale (**20A**) et labiale (**20B**) ; **21**. M2 droite de *Macrocranion vandebroeki* en vues occlusale (**21A**) et labiale (**21B**) ; **22**. P3 d'un rongeur en vue occlusale ; **23**. Talonide d'une m3 droite de rongeur ischyromyidé en vues occlusale (**23A**) et labiale (**23B)**.

St Valery-sur-Somme section dated as “Lower Sparnacian” (Dupuis et al., 1982) in which the CIE has also been recognized (Magioncalda, 2004) and in Lihons (Dupuis et al., 1986).

4.2.3. Vertebrates

Some fish remains have been observed from 0.45 m to 2.55 m. Most of the vertebrate remains are concentrated in a thin layer of 5–8 cm thick located at 2.55 m in a marly level of unit 2 a few centimeters below the thick lignite layer. 400 kg of sediment of this thin vertebrate layer has been screenwashed. Most of the remains are very small, indicating a taphonomic bias. They are not well preserved but some allow identification (Fig. 5).

4.2.3.1. Fish. The fish remains mainly consist of teeth and otoliths. Among the latter, the percoid *Anthracoperca* sp. (Fig. 5.6) is especially abundant. The Osmeridae, a family of salmoniforms, is represented by *Thaumaturus* sp. (Fig. 5.5). Both taxa are known from the Early Eocene of Lihons (Dupuis et al., 1986) and the Middle Eocene of Geiseltal in Germany (Micklich and Gaudant, 1989; Voigt, 1934).

4.2.3.2. Amphibians. Several vertebrae of salamanders are present. Vertebrae with dermal plates and continuous zygapophyseal crests are morphologically close to those of the living genera *Taricha* and *Notophthalmus* from North America (Folie et al., 2009). They are here referred to cf. *Notophalmus* sp. (Fig. 5.7). Another salamandrid with a more typical morphology similar to the genus *Salamandra* is also present (Fig. 5.8). The presence of frogs is attested by a typically anuran ischium and surangular (Fig. 5.9).

4.2.3.3. Squamates. Lizards are documented by several bones including typical ventrally guttered claws (Fig. 5.10). Scincomorph lizards are represented by fragments of dentaries (Fig. 5.11), maxillaries and quadrate osteoderms (Fig. 5.12). Oval osteoderms with a central crest are attributed to anguimorph lizards that may represent necrosaurid varanoids (Fig. 5.13).

4.2.3.4. Crocodilians. Numerous small crocodilian teeth (Fig. 5.14) and rare fragments of osteoderms are present.

4.2.3.5. Mammals. Despite their small number, the remains referred to mammals represent a diversified fauna. The presence of some mammals is only attested by typical claws (Fig. 5.15) and worn indeterminate teeth (Fig. 5.16), whereas other remains are diagnostic and some are indicative of a specific age.

A tiny dentary fragment with the talonid of m2 and a complete m3 of a didelphimorphian marsupial with a relatively low crown, an important paraconid and a small, lingually situated hypoconulid can be attributed to the family Peradectidae (*Peradectes* sp. 1, Fig. 5.17A–B). This species is smaller than all other *Peradectes* species described from Europe and North America with the exception of the recently described *Peradectes gulottai* from the Early Eocene of Virginia (Rose, 2010). The latter has about the same size as *Peradectes* sp. 1 but it is difficult to make a morphological comparison because *P. gulottai* is only known from the upper dentition. An M2 or M3 with a straight centrocrista also belongs to the family Peradectidae but the larger size of this tooth clearly indicates another species (*Peradectes* sp. 2, Fig. 5.18A–B). *Peradectes* sp. 2 is similar in size and morphology to *P. protinnominatus* from the Clarkforkian and Early Wasatchian of the Bighorn Basin and *P. mutigniensis* from the MP8+9 of the Paris Basin (Crochet, 1980). In Europe, the genus *Peradectes* is absent from the Earliest Eocene MP7 faunas of Dormaal (Tienen Formation, Belgium) and Le Quesnoy (Nel et al., 1999), but is mentioned in the localities of Meudon, Fordones and Rians, three localities younger than Dormaal but older than the classical MP8+9 localities of Avenay-Mutigny (Godinot, 1981; Hooker, 1998; Marandat, 1991).

A relatively flat M1 or M2 with developed crests and missing the paracone belongs to a paromomyid plesiadapiform. It resembles both *Ignacius* and *Arcius* based on the robust posterior ridge with a restricted hypocone lobe (Fig. 5.19A–B). Here it is however referred to *Arcius* sp. based on the very short postmetacrista, resulting in a more rounded postero-labial region of the tooth than in *Ignacius*. The fragmentary M1 or M2 from Sotteville-sur-Mer is relatively small and resembles only *Arcius zbyszewskii* from Silveirinha (Estravis, 2000) by the small size and the short and weakly developed postero-lingual cinculum. Other species of *Arcius* are larger, except for maybe some specimens of *A. lapparenti* (Aumont, 2004). Paleocene plesiadapiforms of Europe are only represented by the families Plesiadapidae and Toliapinidae. The earliest confirmed definite Paromomyidae of Europe are known from the Early Eocene MP8+9 of Mutigny, Avenay, Condé-en-Brie and Abbey Wood (Aumont, 2004; Hooker, 1998; Russell et al., 1967) and from the MP7 of Rians (Godinot, 1981), Palette (Godinot, 1984), Fordones (Marandat, 1991) and Silveirinha (Estravis, 2000). However, as for peradectids, paromomyids seem absent in the MP7 faunas of Dormaal and Le Quesnoy.

A talonid of an m1 or m2 with strong hypoconid and high entoconid (Fig. 5.20A–B), and a complete but slightly labially damaged M2 with strong conules and well-developed hypocone (Fig. 5.21A–B) clearly belong to the small erinaceomorph lipotyphlan *Macrocranion vandebroeki*. This species is abundant in the MP7 locality of Dormaal (Smith and Smith, 1995) and also present in the younger MP7 (possibly MP8+9) locality of Meudon in the Vaugirard Formation from the southern edge of the Paris Basin (Aubry et al., 2005; Godinot et al., 1998). This species is absent from the MP8+9 localities of Avenay and Mutigny where two other species are present, *Macrocranion* cf. *nitens* and the larger and more bunodont species *Macrocranion* sp. (Russell et al., 1975; Smith, 1997).

A simple, round P3 (Fig. 5.22) and a talonid of a weakly crested m3 with a small entoconid (Fig. 5.23A–B) attest the presence of a middle-sized rodent. It is here referred to the family Ischyromyidae, the only rodent family known from the Early Eocene of Europe. The specimens lack any derived characters and are generally similar to primitive ischyromyids found in Clarkforkian–Early Wasatchian and in MP7 mammal faunas (Escarguel, 1999; Korth, 1984).

5. Discussion

In this study we recognize the onset of the CIE (from −25.0‰ to −29.6‰) corresponding to the P/E boundary from sample STV'1.07 in unit 1 of the CA Mb in the Sotteville-sur-Mer section. This 4.6‰ $\delta^{13}C_{DOC}$ negative shift falls into the *Peckichara disermas* biozone, which is widely recognized in the Paris Basin. A similar correlation between the CIE and the *P. disermas* biozone has also been signaled in several localities of the Paris Basin such as Limay, Achères and Bougival (Aubry et al., 2005; Sinha et al., 1996; Thiry et al., 2006) but in none of these localities were both the CIE and *P. disermas* recorded in the same section with the exception of the Cap d'Ailly section. Interestingly, at Cap d'Ailly the *P. disermas* biozone is recorded only below the P/E boundary whereas this biozone is recorded below and above the onset of the CIE at Sotteville-sur-Mer and thus crosses the Paleocene–Eocene boundary. The onset of the CIE at Sotteville-sur-Mer is 1.5 m below the microvertebrate level, implying that the mammal fauna is Early Eocene in age. This interpretation is confirmed by the stratigraphic position of the Mortemer Formation and by the typically Early Eocene mammal association.

The mammal assemblage is best correlated with the reference-level MP7 of the mammalian biochronological scale for the European Paleogene (BiochroM'97, 1997). Peradectid marsupials and paromomyid plesiadapiforms are absent from Dormaal, the Suffolk pebble Beds and most likely from Le Quesnoy and could therefore suggest a different type of environment in Sotteville-sur-Mer. However, it could also result from a somewhat younger age for the Sotteville-sur-Mer mammals. This latter interpretation is actually corroborated by the carbon isotope values, as Dormaal is situated at the level of the onset of the CIE (Smith et al., 2006). Moreover, Hooker (1998) mentioned that peradectids and paromomyids are absent from his European Paleocene and Earliest Eocene zone PE I which includes the mammal faunas of Dormaal, Erquelinnes, Try and Suffolk pebble Beds, and that both families only appeared in zone PE II based on the first occurrence of *Peradectes louisi* in Soissons (Soissonnais Formation) and possibly of *Arcius* sp. in Meudon (Vaugirard Formation). Their presence in several MP7 mammal faunas of southern Europe such as Silveirinha, Palette, Fordones, and Rians then suggests that these localities are younger than PE I (Hooker, 1998). Our results agree with Hooker's hypothesis that peradectids and paromomyids would appear only after the CIE in Europe. However, our fossils have been found in the Mortemer Formation and predate the oldest previously known records of these families from the Soissonnais and Vaugirard formations. As a consequence, some localities of southern Europe could be older than originally suggested by Hooker (1998) but still younger than Dormaal and the beginning of the CIE. A detailed study of the PE II mammal faunas, especially that of Meudon, would allow us to identify the post-CIE faunas that are older than the classical MP8+9 localities in northern Europe. The carbon isotope record should also be established for the southern MP7 localities.

Two samples rich in dinoflagellates and pollen have been described from the Sotteville-sur-Mer section (Gruas and Bignot, 1985). According to the description, they were extracted from unit 3 of the CA Mb and from the middle part of the SM Mb. Their composition in planktonic microorganisms was similar and they both contained more than 80% of *Apectodinium* spp., mainly *A. homomorphum* and *A. parvum*. This abundance could be interpreted as the *Apectodinium* acme that is related to the PETM (Crouch et al., 2001; Sluijs et al., 2007). The spore and pollen content of the two samples was also similar with the exception that unit 3 was richer in semi-aquatic grass such as Sparganiaceae and in swamp trees such as Taxodiaceae, representing a shallow marine littoral environment with influx of fresh water. The palynological composition of the middle part of the SM Mb shows a decrease in Sparganiaceae and an increase in Restionaceae, *Carya* and tricolporate pollens representing a more diversified pollen assemblage originating from the nearby environment (Gruas and Bignot, 1985).

The Sotteville-sur-Mer reference section thus documents the progressively marine influence from the base of the continental Mortemer Formation to the top of the brackish-lagoonal Soissonnais Formation in Upper Normandy. The deposits record the Paleocene–Eocene boundary and allow to demonstrate the importance of the *P. disermas* biozone and the *Apectodinium* acme for this time interval. Moreover, they contain Earliest Eocene vertebrates that are younger than the MP7 reference-level of Dormaal but much older than the MP8+9 reference-level of Avenay and of an intermediate age between Dormaal and Meudon, potentially close to the age of the Silveirinha fauna.

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