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–Éocène, 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 pliosiadapiform 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–Éocène inférieur d’Europe sont connus du Centre et de l’Est du Bassin de Paris. Cependant, plusieurs affleurements de cet intervalle de temps sont épars dans 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...
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...
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 Mortemmer Formation, and the SM Mb and CR Mb belong to the Mont-Bernon Group.
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 overlaying 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.

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. 5.
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 \(^{13}\)C in \(^{13}\)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 \(^{13}\)CDOC values range from −24.5‰ to −29.6‰, in agreement with previous studies dealing with the dispersed organic matter at the base of a lignite bed possibly belonging to the base of the complete lignite complex. This high-amplitude excursion is similar 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 (Nittellopis, 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 (Raveline 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 Nittellopis heliceteres.

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) and Bithynella sp. (Fig. 5) are numerous. The sphaerid bivalve cf. Sphaerium sp. is also present (Fig. 5). The malaco fauna is typical of fresh water and the genus Bithynella has been identified in unit 9 of the
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 screened. 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. Vertebræ with dermal plates and continuous zygapophyseal crests are morphologically close to those of the living genera Taricha and Nototaphthalmus from North America (Folie et al., 2009). They are here referred to cf. Nototaphthalmus 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 ischiium 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 didelphiomorph 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 dention. 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. protinomimnatus 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 zbyzewskii 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 Abbé 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 01ytypholophan Macrocranion vandebroekii. 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 STV1.07 in unit 1 of the CA Mb in the Sotteville-sur-Mer section. This 4.6‰ $\delta^{13}$CDOC 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 above 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 (BiochronoM’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 Paleogene 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 lousisi in Soissons (Soissonnais Formation) and possibly of Arcurias 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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