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# First carbon isotope chemostratigraphy of the Ouled Abdoun phosphate Basin, Morocco; implications for dating and evolution of earliest African placental mammals

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ABSTRACT

The well-known Maastrichtian–Ypresian vertebrate-bearing phosphate series, in the Ouled Abdoun Basin, Morocco, is classically dated using regional selachian biostratigraphic zonation. These marine sediments yielded Paleocene and Eocene mammals comprising the earliest known placentals from Africa. This study provides the first insight into the organic carbon isotope chemostratigraphy ($\delta^{13}C_{org}$) of the Moroccan phosphate series and a refined dating of its vertebrate-bearing levels. Four Paleocene–Eocene sections in the NE Ouled Abdoun quarries show consistent $\delta^{13}C_{org}$ long term evolutions, from the base to the top: 1) positive trend in phosphorite Bed IIa, beginning with the lower Bone Bed yielding mammals such as *Eritherium*, *Ocepeia*, *Abdounodus*, *Lahimia*, of early Thanetian and Selandian age; 2) transitional negative trend in the Intercalary phosphorite Beds II/I that includes the *Otodus obliquus* and *Phosphatherium escuilliei* Bone Bed of earliest Ypresian age; 3) negative trend to the lowermost $\delta^{13}C_{org}$ values that are correlative to the early–middle Ypresian interval including ETM 2 and ETM 3 hyperthermal events in the global record; 4) positive trend in chert-enriched facies containing the middle Ypresian EECO global climatic event. Our chemostratigraphic study of the Ouled Abdoun phosphate series provides a new chronostratigraphic framework for calibrating the beginning of the evolution of placental mammals in Africa. The lower Bone Bed level from the Paleocene phosphorite Bed IIa yielding *Eritherium* is not younger than early Thanetian, and is most likely Selandian. The *Phosphatherium* Bone Bed in the Intercalary Beds II/I is earliest Ypresian. The phosphorite Bed 0, from which *Daouitherium* probably came, is early–middle Ypresian, just below the EECO. This suggests that the first large proboscideans evolved after the PETM, during mid-Ypresian warming events. The $\delta^{13}C_{org}$ study does not support the presence of Lutetian in the NE Ouled Abdoun phosphate series and suggests that a noticeable part of the upper Thanetian is absent.



## 1. Introduction

The climate record of the late Paleocene–early Eocene period reveals at least three short global warming events: the Paleocene–Eocene Thermal Maximum (ETM1 or PETM ~ 55.8 Ma; Kennett and Stott, 1991; Zachos et al., 2001), the Eocene Thermal Maximum 2 (ETM2 or H1 event or ELMO ~ 53.7 Ma; Thomas and Zachos, 2000; Stap et al., 2010), and the ETM3 (or "K-event" or "X-event"; ~52.5 Ma; Zachos et al., 2004; Röhl et al., 2007; Agnini et al., 2009; Coccioni et al., 2012).

These events are called hyperthermals or sometimes "greenhouse crises" (Retallack, 2009) and are associated with abrupt and massive releases of $^{13}C$-depleted carbon into the ocean–atmosphere system (Lourens et al., 2005; Stap et al., 2010). They are characterized by an elevated sea surface temperature and by a worldwide synchronous negative excursion followed by progressive recovery of the $\delta^{13}C$ values, called carbon isotope excursion (CIE). The PETM (ETM1) corresponds to major global faunal turnovers, such as a major extinction of deep-sea benthic foraminifera (Thomas, 1998), blooms of the planktic foraminifer genus *Acarinina* (Kelly et al., 1998), distinctive assemblages of calcareous nannoplankton (Bralower, 2002), appearance and rapid

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dispersal of several modern orders of mammals such as the primates, perissodactyls, and artiodactyls (Gingerich, 2006), and an important faunal renewal among elasmobranchs (Cappetta, 1981). The CIE onset of the PETM is also used as the primary stratigraphic criterion to define the Paleocene–Eocene boundary (Aubry et al., 2007). During the CIE of the PETM, the $\delta^{13}C$ values of the oceans and atmosphere decreased rapidly by 3 to 4‰ and returned to initial values over 170 kyr (Röhl et al., 2007; Westerhold et al., 2007).

These short-term (several dozens or hundreds of ky) hyperthermals occurred superimposed in a long term trend (several Ma) of global warming from the late Paleocene to early Eocene, that culminated in the Early Eocene Climatic Optimum or EECO. The latter corresponds to the highest ocean temperatures of the Cenozoic, characterized by minimal $\delta^{18}O$ values (Zachos et al., 2001), and it is characterized by widespread formation of cherts (Muttoni and Kent, 2007). From late Paleocene to early Eocene, the $\delta^{13}C$ values followed a long term decreasing trend, by 3 to 4‰ and reached minimal values below the EECO (Zachos et al., 2008; Coccioni et al., 2012). The quite similar minimal $\delta^{13}C$ values at the PETM and at ETM 2 and ETM3 (close below or at base of EECO), may lead to confusion in stratigraphic interpretation of late Paleocene–early Eocene strata (*i.e.*, hyperthermals *vs* EECO). The minimal $\delta^{13}C$ values of the ETM3 event have been recently dated uppermost NP11 – lowermost NP12, 52.5 Ma (Agnini et al., 2009; Coccioni et al., 2012).

The phosphate basins of Morocco have yielded among the richest marine vertebrate faunas known from the Maastrichtian to the Ypresian. Their fossiliferous phosphate succession records nearly 25 Ma of evolution across the K/Pg and P/E key periods which saw the rise of many major modern vertebrate lineages. Its vertebrate fauna is the subject of a multidisciplinary study by an international team in collaboration with the *Office Chérifien des Phosphates* (http://www2.mnhn.fr/hdt203/info/vertebrates.php; Gheerbrant et al., 2003; Bardet et al., in press). Current studies focus on the Ouled Abdoun basin, the largest phosphate basin from Morocco, which yielded the richest and best preserved fossil fauna.

Since Arambourg (1935, 1952), the stratigraphy of the Moroccan phosphate series, dated Maastrichtian–Ypresian, is only based on the selachians that are the most diverse and abundant local vertebrates.

Here, we measured the isotope ratios of bulk particulate organic carbon ($\delta^{13}C_{org}$) of the Moroccan phosphate series in order to investigate and constrain a framework for carbon isotope chemostratigraphy. Comparing these data to the global isotope record helps to refine the local stratigraphy and the related ages. Such chemostratigraphic approach is pioneering and fully innovative for the Moroccan phosphate basins.

We focused on Paleocene–Eocene high-resolution sections that include mammal levels in the Ouled Abdoun Basin. This study provides new stratigraphical data on the local Paleocene–Eocene fossiliferous phosphate succession, and it allows possible global correlation, independently from lithofacies and faunal assemblages.

## 2. The Ouled Abdoun phosphate basin

### 2.1. Geographical, structural and geological framework (Fig. 1)

The Ouled Abdoun and Ganntour phosphate basins are located in the structural zone of the Western Meseta of Morocco (Fig. 1). Their phosphate sequence extends from the Late Cretaceous to the Eocene. This period of high eustatic levels was marked in Morocco by a large flooding of its Atlantic margin, that resulted in the phosphate deposits of the epicontinental seas of the Tarfaya-Bou Crâa, Ouled Abdoun and Ganntour basins. These basins have among the longest phosphate series known in the Tethyan province, probably in relation to their stable tectonic evolution and to their paleogeographic crossroads position at the NW corner of Africa, between the Atlantic and Tethys seas (e.g., Lucas and Prevôt-Lucas, 1995).

### 2.2. The Ouled Abdoun vertebrate phosphate fauna

The Moroccan phosphate basins preserve an amazingly rich marine vertebrate fauna that lived in Late Cretaceous and Early Paleogene Western African epicontinental seas. Arambourg (1952), who first studied this fauna, described as many as 150 marine species, such as selachians, osteichthyans, crocodyliformes, aquatic squamates (mosasaurids, aigialosaurids and palaeophids), and plesiosaurs.

New fieldworks were made much later, in 1997 and later on, by our Franco-Moroccan team (http://www2.mnhn.fr/hdt203/info/vertebrates.php) in collaboration with the Office Chérifien des Phosphates (OCP). It yielded new fossil discoveries especially for selachians (Cappetta, 1987, 2012; Noubhani and Cappetta, 1997) and tetrapods (Gheerbrant et al., 2003; Bardet et al., 2010). New fossil tetrapod finds include terrestrial and aerial taxa such as Pterosauria, Dinosauria, Aves and Mammalia (placentals) previously unknown in Moroccan phosphate basins. The updated faunal list includes 330 species (Bardet et al., in press). Marine birds and terrestrial mammals were discovered in several levels from the Thanetian and the Ypresian (Fig. 2, F3). Birds are more or less frequent, especially in the early Ypresian level so called *Otodus obliquus* Bone Bed (Fig. 2), in which also occurs the mammal *Phosphatherium escuilliei* (Gheerbrant et al., 2003).

Mammals are much scarcer; they are found as isolated specimens in three bone bed horizons of the Ouled Abdoun Basin (Bardet et al., in press):

- The Selandian–Thanetian lower Bone Bed from phosphorite Bed IIa (Fig. 2, F1; Solé et al., 2009; Gheerbrant, 2009): *Eritherium azzouzorum* Gheerbrant, 2009, *Abdounodus hamdii* Gheerbrant and Sudre, 2001 in Gheerbrant et al., 2001, *Ocepeia daouiensis* Gheerbrant and Sudre, 2001 in Gheerbrant et al., 2001, *Lahimia selloumi* Solé and Gheerbrant, 2009.
- The Thanetian coprolite upper Bone Bed from phosphorite Bed IIa (Fig. 2, F2): *Ocepeia* n. sp.
- The early (earliest) Ypresian *O. obliquus* Bone Bed from the Intercalary phosphorite Beds II/I (Fig. 2, F3; see Gheerbrant et al., 2003): *Phosphatherium escuilliei* Gheerbrant et al., 1996, and presumably *Seggeurius* sp.

Some other mammals such as *Daouitherium rebouli*, *Boualitomus marocanensis*, and an undetermined taxon (ungulate or macroscelidean; Gheerbrant et al., 2003) are described, but their exact stratigraphic level is uncertain. *D. rebouli* probably comes from the phosphorite level 0 (§5.2).

### 2.3. Stratigraphy of the Ouled Abdoun phosphate basin (Fig. 2)

The Ouled Abdoun and Ganntour marine sedimentary series includes the following succession: Cenomanian–Turonian carbonates (marls, evaporites, limestones), Senonian yellow marls and limestones, Maastrichtian–Ypresian phosphate sequence, and Lutetian *Hemithersitea* dolomitic limestone. The phosphate series and/or the Lutetian dolomitic sediments are locally covered by Neogene continental deposits.

The stratigraphy of the Moroccan phosphate series is based on the selachian biozonation of Arambourg (1935, 1936, 1952). As early as 1934, he extensively sampled vertebrate faunas using dry screenings that was at that time an innovative sampling technique. As a result, he identified and dated several successive selachian assemblages such as Maastrichtian, Danian (="Montian"), Thanetian, and Ypresian, by correlation with European faunas and stages. These assemblages are the base of the stratigraphic scale of the Moroccan phosphate sequence. In the Ouled Abdoun Basin, they characterize the following successive phosphorite beds (mining terminology) that are exploited by the Office Chérifien des Phosphates, from top to down (see Fig. 2):

- Phosphorite Bed I: Ypresian;
- Phosphorite Bed IIa: Thanetian;
- Phosphorite Bed IIb: Danian;
- Phosphorite Bed III: Maastrichtian.