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# A complete terrestrial Oligocene magnetobiostratigraphy from the Ebro Basin, Spain

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## Abstract

The integrated litho-, bio- and magnetostratigraphic cross-correlation of 11 continuous and correlatable sections in the southeastern Ebro Basin (NE Spain) produced a complete Oligocene magnetic polarity stratigraphy ranging from latest Eocene to earliest Miocene. The magnetic polarity zonation of the different alluvial and shallow lacustrine sections has been correlated to the GPTS using fossil mammals and the distinct sequence and pattern of polarity reversals. The composite magnetic polarity sequence defines a continuous sequence from Chron C15n to Chron 6Cn.2n, from 34.8 to 23.7 Ma (late Eocene–early Miocene). In addition, a few short normal and reverse polarity events that correlate to cryptochrons in the GPTS are found (i.e. in C11n.1r and C8n.1r). The resulting regional magneto-biostratigraphic framework based on fossil mammals is proposed to refine the dating of the European Oligocene biochronological mammal Paleogene units and correlate them with the standard Oligocene marine stages and the North American land mammal ages. The magnetostratigraphy now established enables more precise dating of the late Eocene and Oligocene paleofloristic and paleofaunistic changes in southwestern Europe, which were coeval to ongoing global paleoclimatic and paleoceanographic changes on Earth caused by high latitude cooling and ice sheet development in eastern Antarctica. © 2001 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

Fossil land mammal studies are among the most efficient tools to date and correlate non-marine Tertiary successions (see e.g. [1–3]). Never-

theless, the fossil mammal record is usually restricted either to isolated horizons or lenses in stratified records or to discontinuous karstic infills. This discontinuous record has often hampered the use of the standard biostratigraphic approach (which is based on the establishment of the stratigraphic ranges of fossil taxa in thick and continuous successions), and has enhanced the so called biochronologic approach, which has been extensively developed both in North America [1–3] and in Europe [4,5], where Paleo-

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gene and Neogene mammal biochronological subdivisions (the so called MP and MN units) have been revised in the last decades. Despite these difficulties, the interest to apply rigorous biostratigraphic criteria in the definition of mammal biozones, and even stages, is increasing due to the need for more refined dating in high resolution studies of terrestrial paleoenvironmental records. This fact, together with the more generalized availability of radiometric dating and magnetic stratigraphy, has enabled significant advances in

the study of terrestrial records both in North America [2,3,6] and in Eurasia [7–11].

Litho- and biostratigraphic studies carried out on the continental sequences of the southeastern Ebro Basin (NE Spain) have shown that accurate magnetostratigraphic studies can be carried out on continuous, widely exposed successions, which cover most of Paleogene to Neogene times (see [12] for a review). Moreover, the large number of fossil mammal localities and more punctual palynological data makes the Ebro Basin an un-

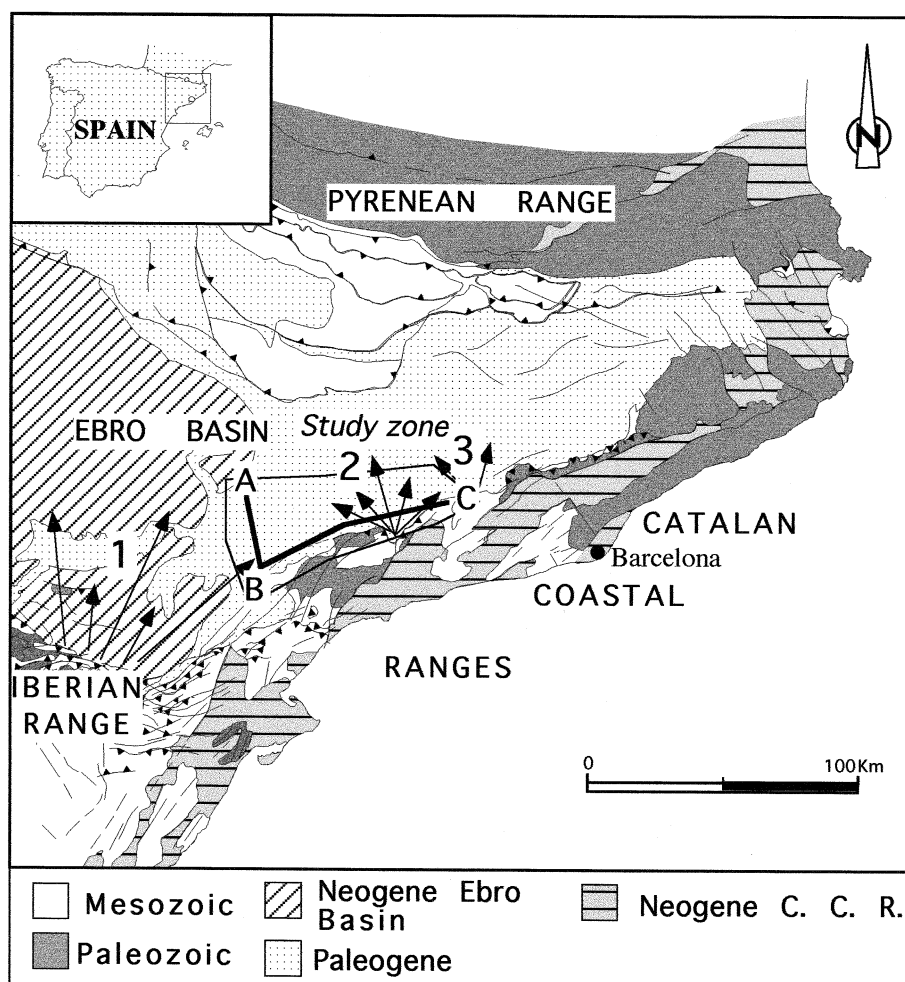


Fig. 1. Geological setting of the study area in the Ebro foreland Basin (NE Spain). The line A–B–C corresponds to the composite, synthetic stratigraphic panel of Fig. 2. Numbers in the figure correspond to the main alluvial systems in the area: (1) Guadalope–Matarranya alluvial system, (2) Montsant alluvial system, (3) St. Miquel de Montclar alluvial system (see Fig. 2 for stratigraphic location).

usual case in Europe where a continuous, non-marine late Eocene–Miocene stratigraphic succession can be accurately biozoned [12,14]. Therefore, integrated litho-, bio- and magnetostratigraphic research focused on these Paleogene and early Neogene sections for obtaining a highly resolute magnetostratigraphy, a more precise chronology of the latest Eocene–Oligocene bioevents in NE Spain (and by extension in SW Europe), and their correlation with the coeval global changes on Earth.

## 2. Geological, paleogeographic and paleoclimatic setting of the Ebro Basin

The Cenozoic Ebro Basin, in the northeastern part of the Iberian plate, is the late Eocene–Miocene southern foreland basin of the Pyrenees [15,16]. This basin is bound by three mountain

ranges which were built up mainly during Eocene–Oligocene compression: the Pyrenean orogen to the north, the Iberian Range (IR) to the southwest and the Catalan Coastal Ranges (CCR) to the southeast (Fig. 1). The Pyrenees exerted the major control on overall basin evolution, causing lithospheric flexure by the tectonic load and giving rise to varying subsidence rates (initially larger near the range than in the southern foreland zones). Nevertheless, sedimentation in the eastern Ebro Basin zones was clearly modified by tectonics along the IR and CCR [17,18]. From late Eocene to late Miocene, the Ebro Basin displayed a closed drainage and its main depositional framework consisted of distributive alluvial systems fed from the tectonically active surrounding ranges, laterally grading via carbonate- and evaporite-dominated, perennial to ephemeral shallow lacustrine zones. Up to 2000 m of upper Eocene to lowermost Miocene alluvial–lacustrine successions

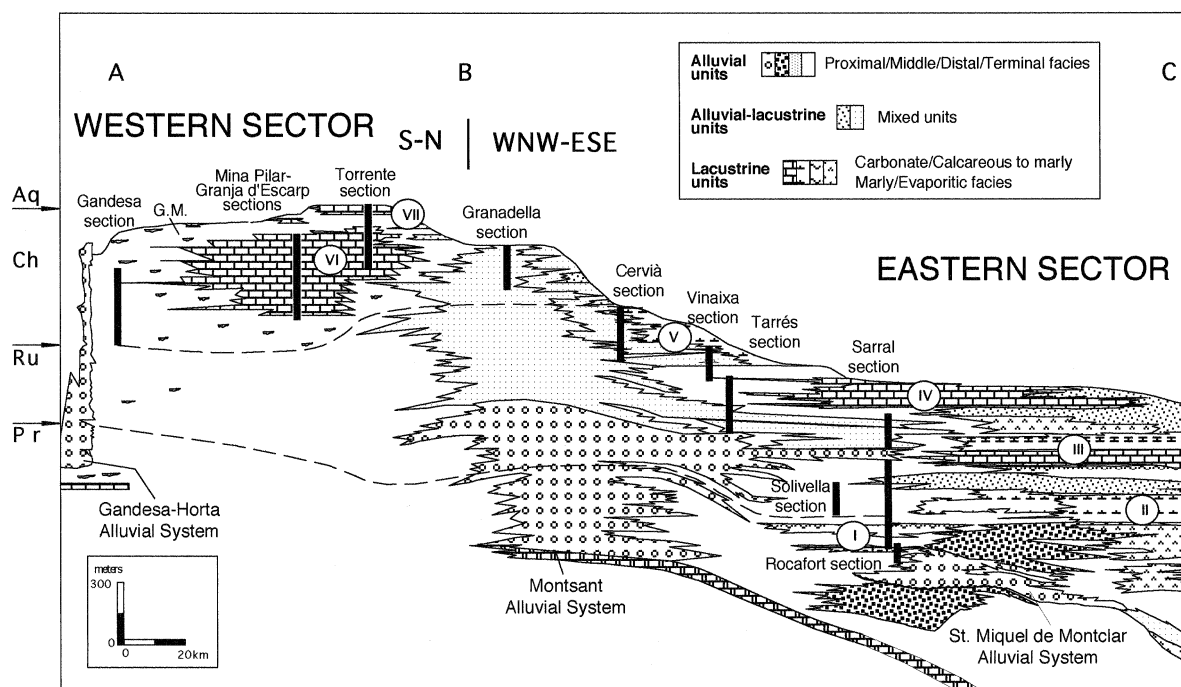


Fig. 2. Composite, synthetic stratigraphic panel of the SE Ebro Basin marginal zones with the magnetostratigraphic sections plotted (see Fig. 1 for location of A–B–C). The roman numerals refer to the lacustrine systems mentioned in the text. I, Noguera; II, Anoia; III, Segarra; IV, Urgell; V, Garrigues; VI, Mequinenza; VII, Torrente. Pr, Priabonian, late Eocene. Ru, Rupelian, early Oligocene. Ch, Chattian, late Oligocene. Aq, Aquitanian, early Miocene. Notice the changing orientation of the panel and the trace of the time lines, caused by varying sedimentation rates.

accumulated in the eastern Ebro Basin (Figs. 1 and 2).

Palinspastic plate reconstructions and paleomagnetic data suggest that during Eocene and Oligocene times the Iberian Peninsula was located slightly south of its present latitude (40°N). Climatic regimes in the region were warmer than present, tropical and likely submitted to cyclical variations in aridity [17]. Under this situation the Iberian Peninsula was affected by the global late Eocene climatic cooling [19] and its climate shifted from early–middle Eocene equant warm, humid conditions to more pronounced dry–wet seasonality in the late Eocene–early Oligocene.

This paleoclimatic trend had been documented by paleoclimatic proxies recorded in the Ebro basin, i.e. fossil palynomorphs, plant macrorests, mammals and reptiles [12,14,20], although their chronological attribution and linking to the global climatic events was only approximate. Precising the chronological framework where the successive floral and faunal bioevents took place was one of the main aims of our multidisciplinary approach.

### 3. Sampled sections

The present magnetostratigraphic study com-

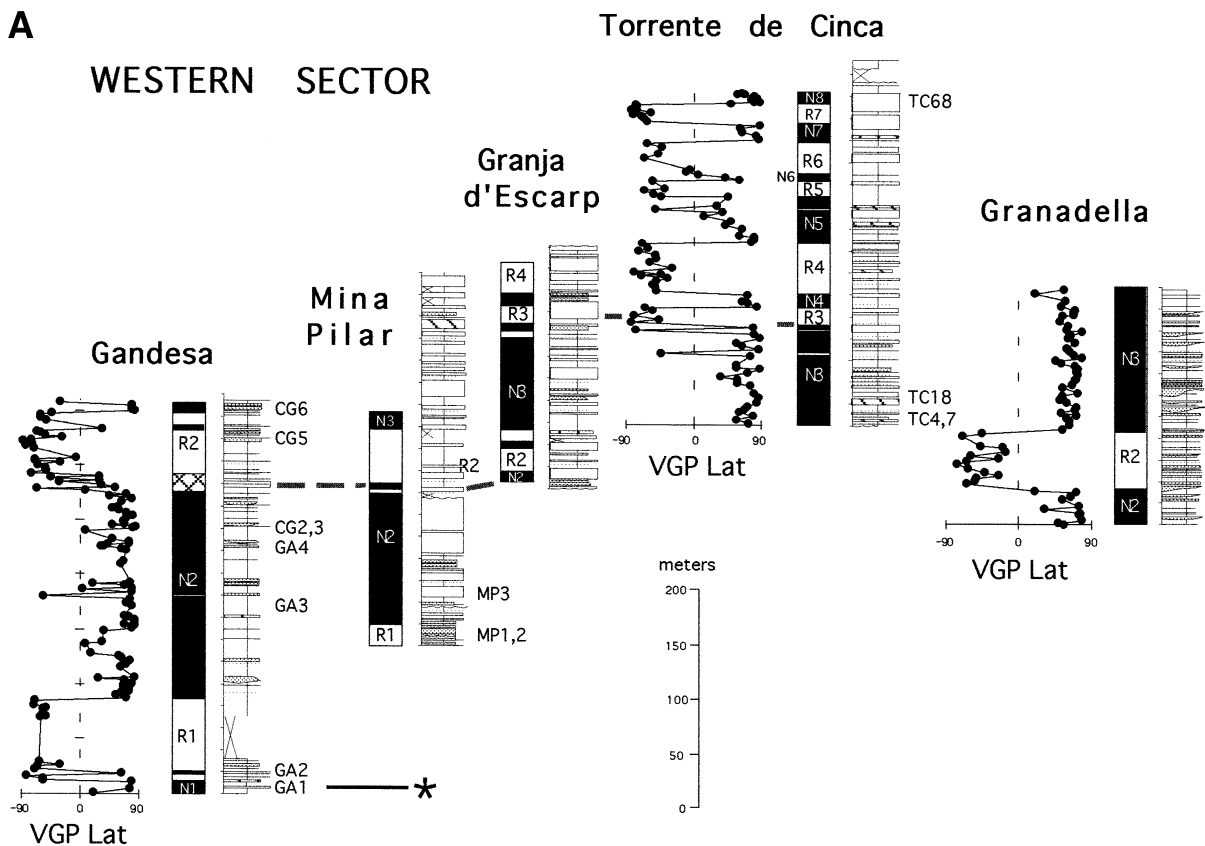
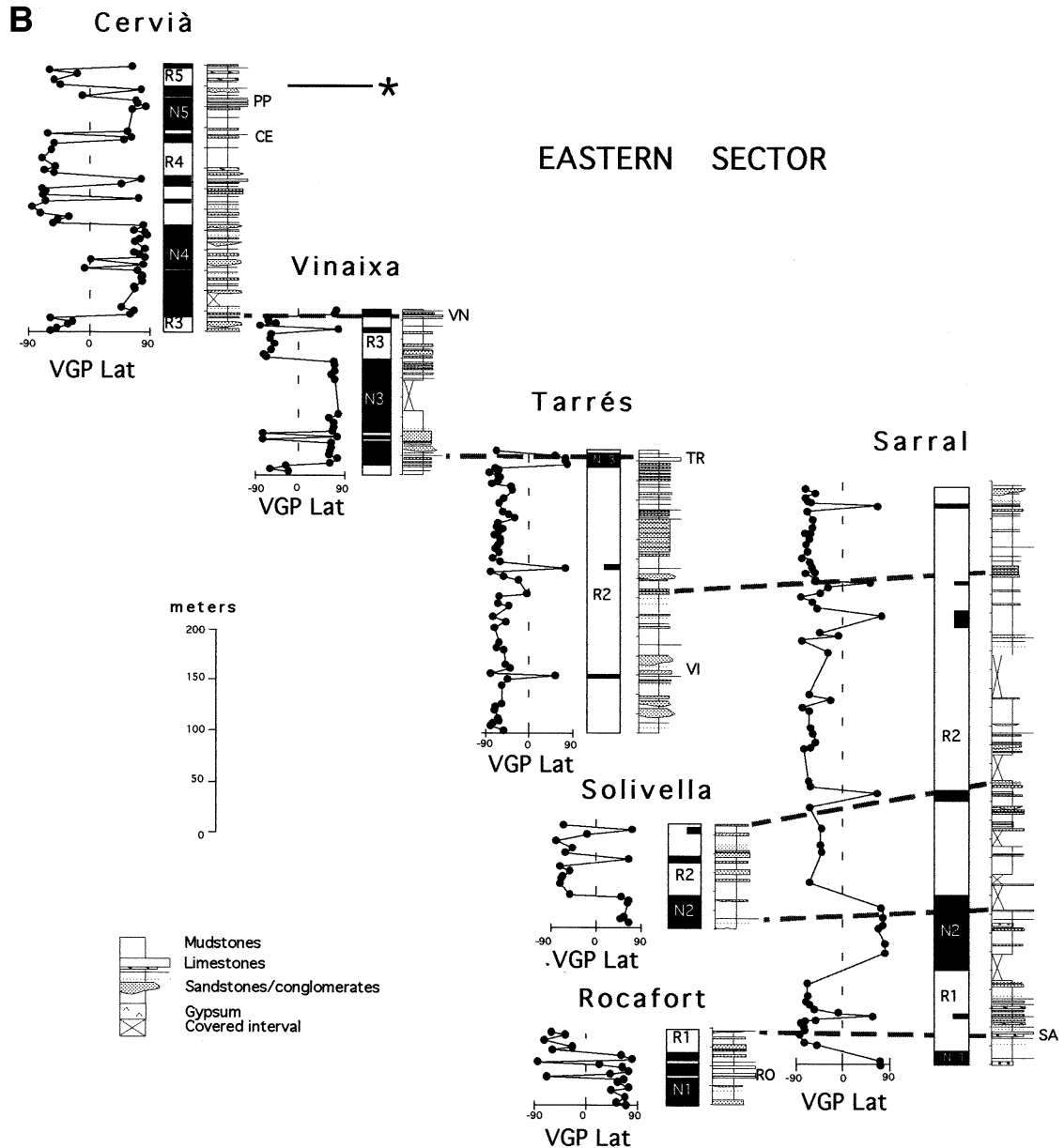


Fig. 3. Local litho- and magnetostratigraphic sections from the western (A) and eastern (B) sectors of the study area. Positive and negative VGP latitudes (dots) represent normal and reversed polarities, respectively. The locations of main fossil mammal and plant sites are indicated. RO, Rocafort. SA, Sarral (macroflora). VI, Vimbodí. TR, Tarrés. VN, Vinaixa. CE, Cervià. PP, Pla del Pepe. GA, Gadesa. CG, Coll d'en Grau. MP, Mina Pilar. TC, Torrente de Cinca (see Fig. 5 for complementary information on fossil localities). Stars in CE (Eastern sector) and GA (western sector) sections indicate the magnetostratigraphic correlation between both sectors. Gray lines between sections in the eastern sector correspond to key-bed correlation. TC section after [26]; Mina Pilar and Granja d'Escarp sections after [28].

prises 11 stratigraphic sections from two (eastern and western) sectors in the SE Ebro Basin. A solid correlation between these sections was established and was the basis for anchoring the resulting magnetostratigraphic successions. Biostratigraphic and magnetostratigraphic data, supported by mapping and physical key-bed cor-

relations, allowed us to build a composite section for each sector (Figs. 2 and 3).

The sections of the eastern sector, encompassing 1100 m of thickness, were sampled along the southeastern basin margin. These sections correspond to intermediate to marginal facies of the St. Miquel de Montclar and Montsant alluvial sys-



tems, interfingering with the lacustrine facies of the Anoia, Segarra, Urgell and Garrigues systems (Figs. 1 and 2). Alluvial sediments consist of isolated sandstone and conglomerate channel-fill bodies, interbedded with mudstone-dominated, overbank deposits and sheet sandstones or thin, gently incised, channel-shaped bodies. Lacustrine facies consist of single beds and packages of lacustrine carbonates, ranging from a few centimeters up to several meters thickness and interbedding with gray lacustrine marls. Correlation among sections is based on lithostratigraphic and photogeological mapping of some noticeable, laterally continuous lacustrine carbonates and alluvial, tabular-bedded units, which can be traced between sections (Fig. 3). The established mammal biozones in this sector range from late Eocene to lowermost late Oligocene and are based on 18 mammal sites, which are included either in the magnetostratigraphic sections or are correlatable to them.

The sections of the western sector were sampled from the basin margin to the inner basin and covered about 700 m in thickness. One of them (Gandesa (GA) section) includes distal facies of marginal alluvial fans (GA–Horta System) and distal facies of the Guadalupe–Matarranya fluvial megafan (Figs. 1 and 2). The medial–distal fluvial facies of the Granadella section belong to the Montsant fluvial megafan. Finally, the remaining sections are included in zones of interfingering between the distal mudstone–sandstone facies of the diverse fluvial megafans (Guadalupe–Matarranya and Montsant) and the carbonate-dominated deposits of inner lacustrine zones. The alluvial facies are similar to those in the eastern sector. Lacustrine facies include limestones and build up thick successions grading laterally into interbedded carbonate- and mudstone-dominated successions (Figs. 2 and 3). Therefore, correlation among magnetostratigraphic sections, from the basin margins to the inner basin zones, is based on several intermediate, up to 500 m thick, stratigraphic sections, that correlate to each other thanks to significant carbonate key units (see VI and VII in Fig. 2). The established mammal biozonation in this sector ranges from lower Oligocene to lowermost Miocene and is supported by

35 mammal sites located either in the magnetostratigraphic reference sections or in correlatable sections.

The correlation between eastern and western sectors was made by means of intermediate lithostratigraphic sections, which enabled physical correlation from the top of the Cervià (CE) section (eastern sector) to the Granadella and the Mina Pilar sections (western sector). In addition, magnetostratigraphy supports lithostratigraphic correlations.

#### 4. Biostratigraphy

Biozonation of the upper Eocene–lower Miocene successions in the SE Ebro Basin was developed on the basis of their fossil mammal assemblages [12,14]. New biostratigraphical sampling through the studied sections resulted in 19 new Oligocene mammal sites, in addition to classical localities, with a total of 53 mammal sites. The new rodent fossil material gathered from revisited and new localities improved the biostratigraphic framework [12].

The Ebro Basin biozonation consists of 11 local zones: *Theridomys golpeae*, *Theridomys* aff. *aquaticus*, *Theridomys calafensis*, *Theridomys major*, *Blainvillimys blainvillei*, *Eomys zitteli*, *Eomys major*, *Eucricetodon dubius*, *Eucricetodon robustus*, *Rhodanomys transiens* and *Vasseuromys* sp. zones [12,14]. These zones occur in the studied interval, ranging without stratigraphic gaps from the latest Eocene to the earliest Miocene and cover the whole Oligocene time span. This time range would be approximately coeval with that encompassed between the late Eocene MP-19/20 mammal unit (*T. golpeae* local zone) and the early Miocene MN-1 mammal unit (*Vasseuromys* sp. local zone). The mammal faunas that characterize the local biozones in the Ebro Basin are not always closely coincident with those of the European MP biochronological units, since the former correspond to real biostratigraphic units. Moreover, the Ebro Basin local biozones do not include all the fossil mammal species recorded in other western and central European assemblages [4], likely due to differing paleobiogeography. In

spite of that a well-constrained correlation could be established for the sake of anchoring the resulting magnetostratigraphic successions [12,14].

## 5. Paleomagnetic analysis and magnetostratigraphy

Paleomagnetic samples of all rock types were collected using a standard gas-powered drill machine. Locally oriented blocks of poorly consolidated layers (mudstones) were collected, solidified and drilled in the laboratory. Paleomagnetic measurements were performed at the Laboratory of Paleomagnetism of the Institute of Earth Sciences 'Jaume Almera' (UB-CIRIT-CSIC) in Barcelona (Spain).

Approximately 560 magnetostratigraphic sites were sampled along 1800 m of stratigraphic sections. More than 1500 specimens were stepwise thermally demagnetized following standard procedures, and virtual geomagnetic pole (VGP) latitudes were used to establish the magnetic stratig-

raphy. The magnetic record of the distinct lithologies is highly variable, especially concerning the stability of the primary component. The natural remanent magnetization was measured using a three-axes GM400 CCL cryogenic magnetometer housed in a three-pair Helmholtz coil; a Kappabridge KLY-2 was used to measure changes in the bulk susceptibility. Stepwise demagnetization of samples was carried out by means of a Schonsted TSD-1 furnace and a GSD-5 tumbling AF demagnetizer.

Generally, three samples per stratigraphic layer at 4 m average site intervals were taken and thermally demagnetized in steps of 50°C (Fig. 4). Characteristic remanent magnetization directions were calculated by means of principal component analysis [21], from visual inspection of the demagnetization diagrams. Secondary viscous magnetization conforming to the present-day field or acquired during sampling and/or storage was removed by heating to ~300°C. A characteristic component of either normal or reversed polarity is typically recognized at higher temperatures in

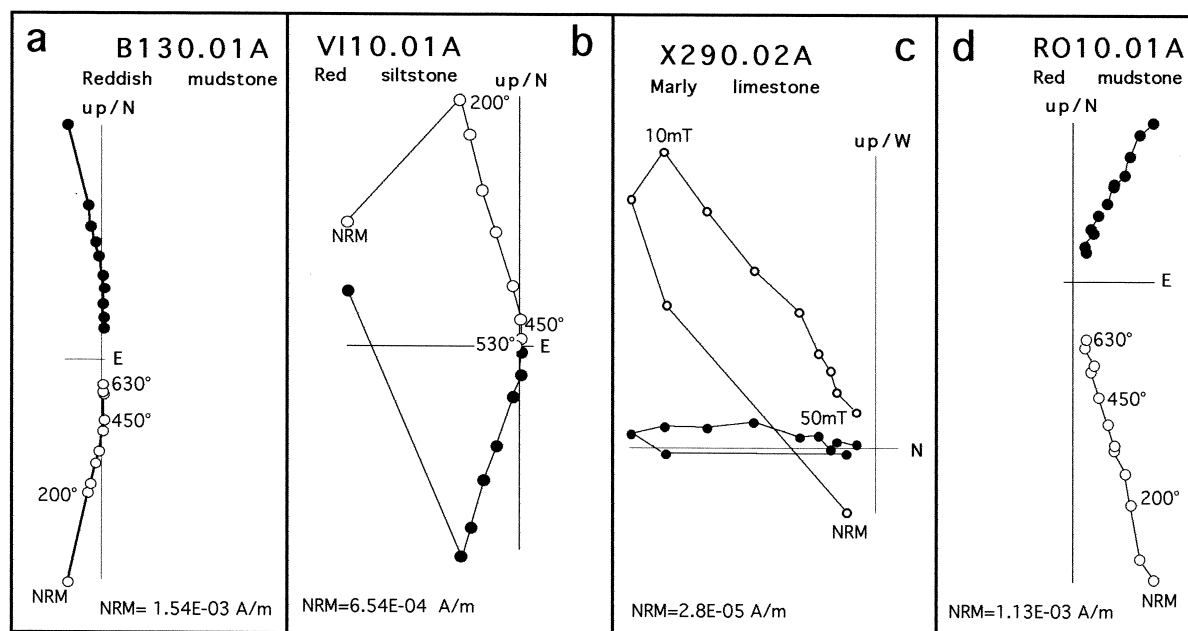


Fig. 4. Demagnetization diagrams of representative samples: (a) and (d) correspond to reddish and red mudstones and display normal polarity; (b) and (c) correspond to red siltstone and marly limestone facies, respectively, and are reversed. Temperature steps in °C for samples (a), (b) and (d); AF field in mT for sample (c). Sample lithology is also indicated in each diagram.

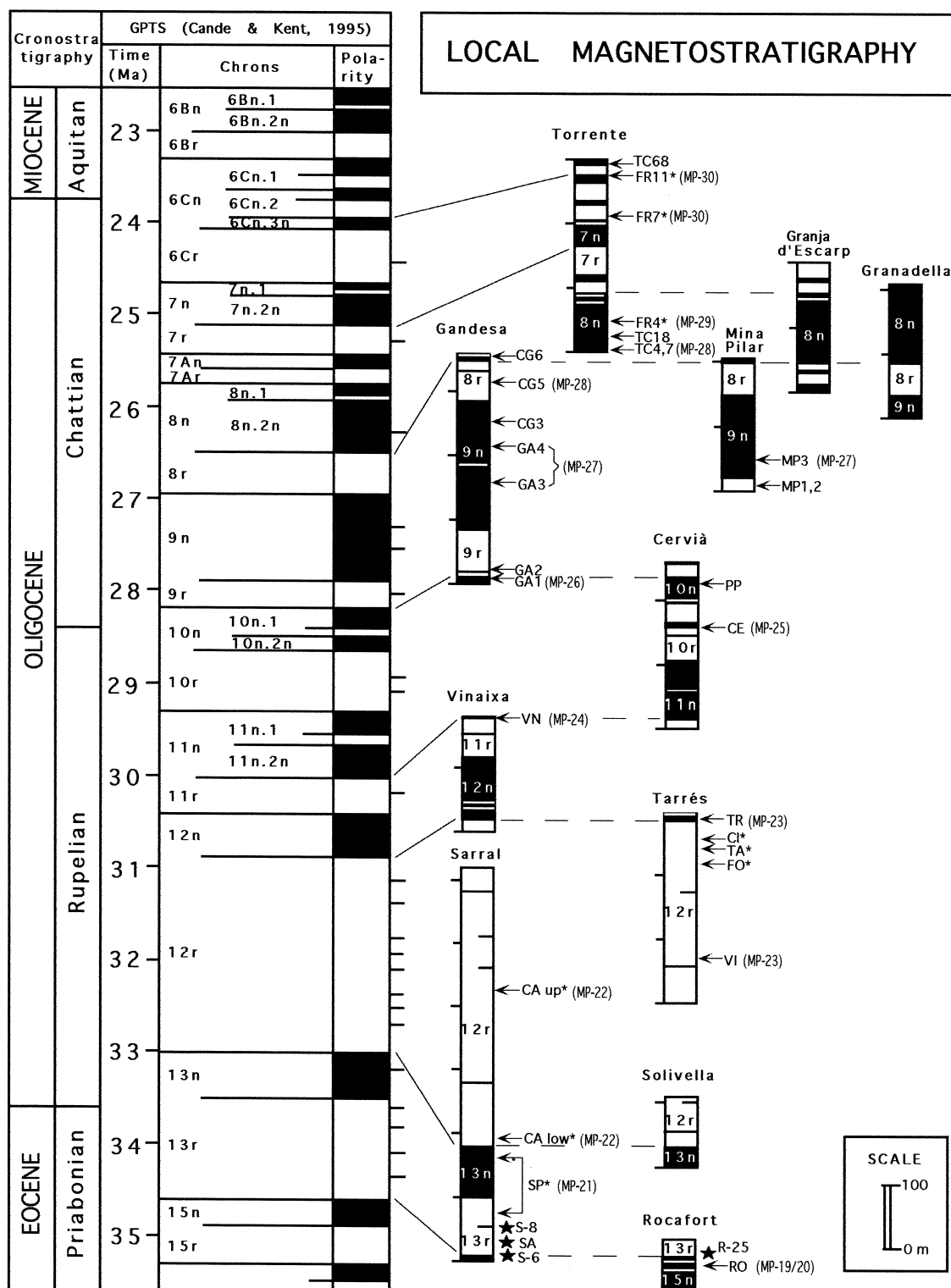




Fig. 5. Correlation of all the magnetic polarity sequences to the GPTS with indication of mammal sites and their attribution to the diverse MP biochronological reference levels. RO, Rocafort. SP, Santpedor. CA low, lower Calaf localities. CA up, upper Calaf localities. VI, Vimbodí. FO, Forés. TA, Tàrraga. CI, Ciutadilla. TR, Tarrés. VN, Vinaixa. CE, Cervià. PP, Pla del Pepe. GA, Gandesa. CG, Coll d'en Grau. MP, Mina Pilar. FR, Fraga. TC, Torrente de Cinca. Asterisks indicate fossil mammal localities correlated to the magnetostratigraphic section. Stars indicate the palynomorph (R-, Rocafort de Queralt and S-, Sarra) and macroflora (SA, Sarra) localities which record a major paleofloral change [30].

most of the studied samples. The unblocking temperatures and IRM analyses indicate the presence of magnetite and hematites as main remanence carriers.

Sediments from the SE Ebro Basin are not significantly deformed in the sites studied, with beds only slightly tilted to the northwest, and thus a fold test is not significant. Therefore the reliability of the magnetostratigraphic results is based mainly on the consistency of the combined litho-, bio- and magnetostratigraphic cross-correlation through the sections. For each sampling level, the mean VGP latitude has been calculated, enabling the establishment of a scale of normal and reversed magnetozones. Thus, the polarity pattern of each section comes from the position of the mean pole paleolatitude for each side.

The magnetic polarity zonation of the different sections was correlated to the GPTS using the distinct sequence and pattern of polarity reversals after age approximation by fossil assemblages. The occurrence of very short subchrons has not been taken into account for magnetostratigraphic correlation.

The sequence of VGP latitudes in the eastern sector (Figs. 3 and 5) shows five normal (N1–N5) and five reversed (R1–R5) magnetozones. The pattern of magnetozones of the composite section of the eastern sector indicates the occurrence of a very long distinctive reversed interval (R2) documented in the Sarra (SA), Solivella and Tarrés (TR) sections (Fig. 3). The upper part of the TR section is dated as early Oligocene (*T. major* zone, MP-23) thanks to the TR fossil site, and from correlation with the nearby localities of Tàrraga, Ciutadilla and Forés [15]. The lower part of the TR section is also dated early Oligocene by means of the Vimbodí (VI, MP-23) site [22]. In addition, the lower part of the SA section can be closely correlated with the Calaf localities assemblage

which is early Oligocene in age as well (MP-22 reference level in [4]). On the basis of both faunal assemblages and local magnetostratigraphic correlations, we conclude that R2 reversed interval is unambiguously early Oligocene. Other significant new mammal sites, Vinaixa (VN) and CE, also indicate early Oligocene age ranging from MP-24 to MP-25 [12]. Moreover, the older Rocafort (RO) mammal site, located in the N1 magnetozones of the RO section, records the presence of the *T. golpeae* local zone [13,23] of late Eocene age. According to faunal evidence, most of the magnetostratigraphic composite section of the eastern sector ranges from latest Eocene to early Oligocene (i.e. MP-19/20 to MP-25), with the transition to late Oligocene being probably present (PP locality).

In the western sector (Fig. 3), the sequence of VGP latitudes shows eight normal (N1–N8) and seven reversed (R1–R7) magnetozones. The fossil sites of GA (GA1, 3 and 4) and Coll d'en Grau (CG3, 5 and 6) occur in the GA section and are related mainly to R1–R2 and lower N3 magnetozones. These magnetozones would be early late Oligocene since they range from the *E. zitteli* zone (MP-26 reference level, [4]), to the *E. dubius* zone (MP-28 reference level, [4]). Other fossil sites, like Mina Pilar, Torrente de Cinca (TC) 4, 7 and 18, Fraga 4, 7 and 11 and TC68 range from MP-27 to MP-30 reference levels [4,13,14,24,25]. The Mina Pilar, Granja d'Escarp and Granadella sections span R1–R4 magnetozones. The TC completes this succession since it spans N3–N8 magnetozones. According to the available biostratigraphic information and following previous magnetostratigraphic work on the Torrente section [26], these magnetozones span the late Oligocene to the early Miocene, with the boundary being located at N8 (Figs. 3 and 5).

According to this data set, the entire composite

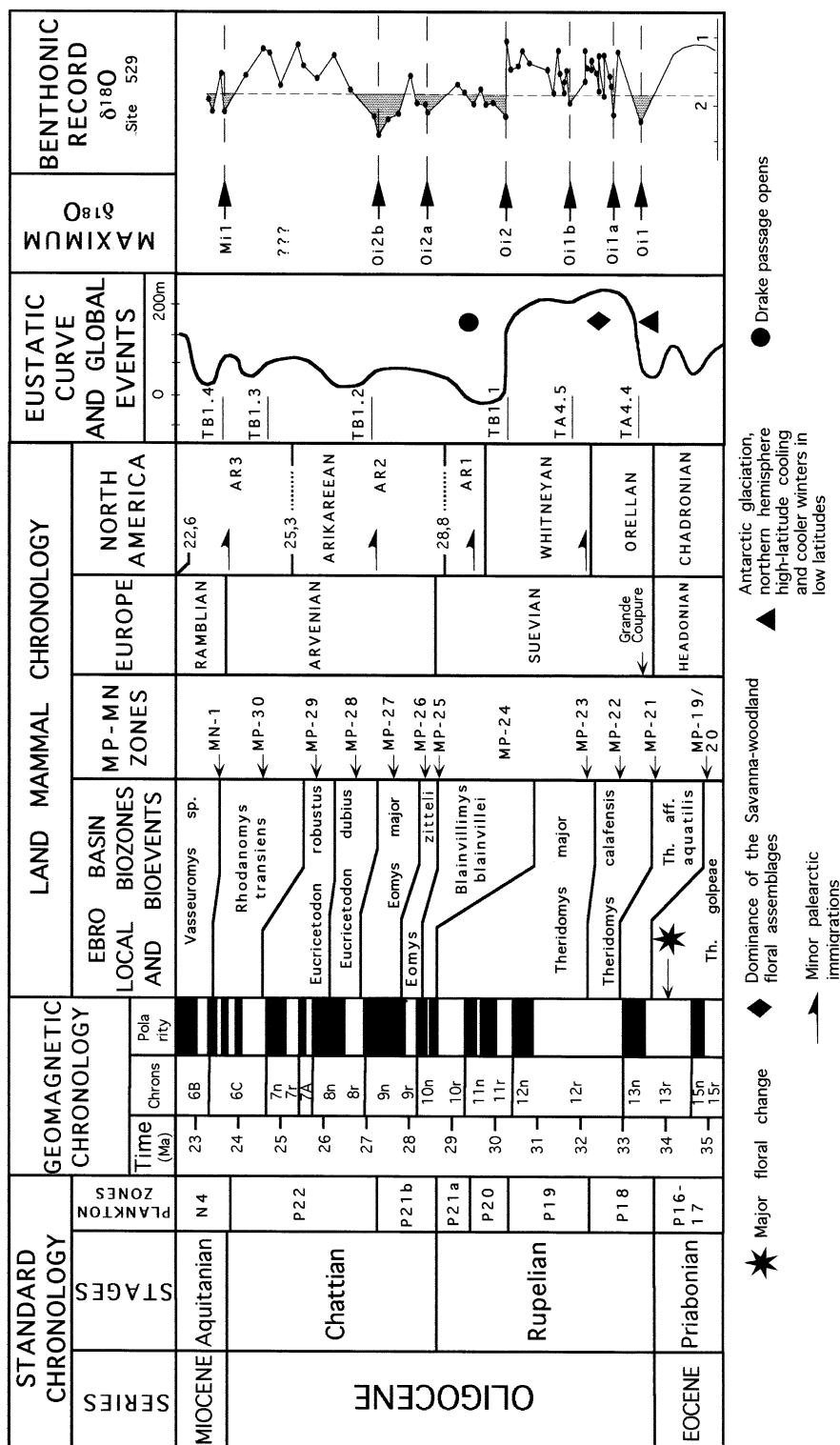


Fig. 6. Chronology of the local mammal biozones in the SE Ebro Basin and their correspondence to MP–MN mammal units, the North American land mammal ages and the standard chronostratigraphic units. Notice the correlation of the MP chronological units to the geomagnetic scale, with arrows indicating their position in relation to the local biozones. The major floral change which affected NE Spain in the latest Eocene and some of the later major faunal turnovers were coeval to significant isotopic shifts, which record global paleoceanographic and paleoclimatic changes related to the transition to glaciated Earth. Based on [1–4,29,39–41,46].

magnetostratigraphic succession ranges from late Eocene to early Miocene and thus a complete record of Oligocene time is spanned in this study.

## 6. Correlation to the GPTS

The correlation of these sections to the GPTS is based on the long, distinctive pattern of local magnetozones, as well as on the faunal associations distributed throughout the late Eocene to early Miocene succession. Within these constraints, the correlation of the magnetostratigraphy successions to the GPTS [27] is best established by anchoring the distinctive long interval of reverse polarity (R2) recorded in the SA, Solivella and TR sections to Chron C12r (Fig. 5), early Oligocene age. As a consequence of this anchorage, the normal magnetozones N2 of the lower part of the SA and Solivella sections below the long distinctive C12r reversed Chron, corresponds to the Chron C13n. Following downwards, the Chron C13r (SA and RO sections) and the Chron C15n (lowermost part of the SA section and RO section), are late Eocene in agreement with the age (MP-19/20) of RO mammal site (Fig. 5).

From the long, distinctive reversed Chron C12r recorded in the TR section and continued in the lower part of the VN section, it is possible to identify in this sequence the chrons C12n, C11r and C11n (Fig. 5). The chrons C11r and C11n are also present in the CE section. It is possible to distinguish, in the middle part of the Chron C11n, a short reversed interval that probably corresponds to the Chron C11n.1r. Under this hypothesis the CE section includes chrons C11r, C11n.2n, C11n.1r, C11n.1n, C10r, C10n and C9r (Figs. 2, 3 and 5).

In the western sector, the long normal interval N2 recorded in the GA section (Fig. 5) is used as an anchoring reference and, using the attribution

of GA1 mammal site as early late Oligocene (i.e. MP-26), this interval corresponds to the Chron C9n. From this point the reversed interval located below corresponds to the Chron C9r, recorded also partially in the upper part of the CE section (eastern sector). The Mina Pilar–Granja d'Escarp [28] and Granadella sections also record (total or partially) the Chron C9n and complete the GA section range, from Chron 8r to 7r. The sequence in this sector is finally completed by the Torrente section [26] with the occurrence of chrons C8n through C6Cn.2n (Figs. 3 and 5).

Notice that not only all of the GPTS chrons have been registered along the studied sections, but also some subchrons (Figs. 3 and 5). Some of these subchrons can be tentatively correlated to those established [29] (C11n.1r and C8n.1r subchrons). Others are not reflected in the oceanic record of this reference scale (i.e. reversed subchrons in C15n or C12n or the normal subchron in C8r, recorded in two different sections). Further investigations are required to establish their significance (local remagnetization, intensity fluctuations, short geomagnetic events). Nevertheless, the relatively rapid sedimentation rate (11 to 26 cm/kyr) of the different sections [12,26,28] may account for the recording of short subchrons otherwise unrecognized in the oceanic record.

## 7. Chronology of the major bioevents, correlation to global processes and intercontinental correlation

The correlation here proposed between the GPTS and the local magnetostratigraphy is based mostly on the available fossil mammal data [12,14,15], which constitute the main reference for anchoring the local magnetostratigraphy to the GPTS (Figs. 5 and 6). Each local biostratigraphic subdivision can be related confidently to

the corresponding MP biochronological unit and in its turn the latter can be referred to a single chron or a restricted range of chrons. A more precise correlation to the marine planktonic biozonations and the marine standard stages also arises from this correlation (Fig. 6).

The first major bioevent recognized in the late Eocene–early Miocene succession studied in the SE Ebro Basin is a floristic event recorded low in the section by changes in the palynomorph associations, with a first widespread appearance of characteristic grassland taxa (Gramineae, *Phlo-mis*, Caryophyllaceae) and an early noticeable decline of typical tropical forest forms [20]. Similar changes in the terrestrial flora during the Eocene–Oligocene transition have been documented worldwide. High to medium latitude floral changes in the Northern hemisphere have been well-recognized in North America [29,30]. In Europe, on the base of mega-floral and pollen data [31,32], a change from middle Eocene tropical floras to taxodiaceous swamps and reed marshes is detected at the Eocene–Oligocene boundary. In the Southern hemisphere [33,34], a decline in plant community diversity is documented by the late Eocene, followed by an Oligocene low diversity vegetation characteristic of cooler temperate climates. The now available magnetostratigraphic data in the Ebro basin point to a similar paleofloristic change in Iberia in the middle part of C13r (i.e. about 34 Ma) and reflects a similar regional paleofloral turnover [29–32]. This constitutes one of the first well-dated terrestrial records in southwestern Europe of the ongoing global climatic and paleoceanographic changes which affected Earth during late Eocene times [35–40]. This floristic change was coeval to the high latitude cooling, the cooler winters in lower latitudes and the positive isotopic shift [37–41] which heralded the Oi1 isotopic event attributed to the maximum development of the Eastern Antarctic ice sheets (Fig. 6).

The above mentioned floristic changes were related to the set of successive environmental, climatically forced changes that led to a major earliest Oligocene faunal turnover in western Eurasia, known as the ‘Grande Coupure’ [2,3,35]. In the southern Pyrenean zones and in

the Ebro Basin the mammal fauna changes related to climatic degradation can be traced in a number of late Eocene–earliest Oligocene sections and sites. Thus, the early late Eocene is represented by a number of rich, well-known localities, such as Sossís and Roc de Santa [42], characterized by high diversity in theridomorph rodents (up to four species in the locality of Sossís). This diversity decreased in the late Eocene *T. gol-peae* zone (Sant Cugat de Gavadons, Rocafort de Queralt, MP-19/20) where only one theridomorph species is recorded. The earliest Oligocene levels of the *T. aff. aquatilis* zone (MP-21) are characterized by the FAD of the cricetid *Atavocricetodon*, although the rodent association continued to be dominated in number of individuals by the theridomorphs (*T. aff. aquatilis*, *Pseudotimomys gaillardi*). This first appearance of cricetids in the Paleogene successions of the Ebro basin would record the ‘Grande Coupure’. Taking into account both magnetostratigraphic and biostratigraphic constraints this event should take place around Chron 13n and it was nearly coeval to the isotopic event Oi1 [37,39,40]. This age would be in accordance with that proposed in other Western European zones [43].

After a period of gentle faunal changes (*T. calafensis* and *T. major* zones, MP-22 and 23), very few earlier Oligocene rodent species persisted in the late Oligocene Ebro basin record. This faunal change was significant since it has been recorded in other Iberian basins [44]. The currently available information does not enable prediction of either the character (sharp or gentle) or the age of this late early Oligocene faunal change, but it can be bracketed between the top of Chron 12r and the middle to upper part of Chron 10r. The isotopic event Oi2 is included in this time range [37–40] but no accurate correlation can be proposed between both events.

Thus, early to late Oligocene transition is characterized by a significant decrease in the abundance of the theridomorphs, while cricetids and eomyids became the dominant rodent families in the early late Oligocene (*E. zitteli* zone, MP-26). The diversification of Eomyidae and Cricetidae forms continued through the late Oligocene (Fig. 6). Nevertheless, in the early late Oligocene at

about 26.0 Ma (upper part of Chron C8n.2n) a significant increase in the diversity of large cricetid species took place in the Ebro Basin with two new species: *Cincamyarion giganteus* and *E. robustus* [14]. After the *E. robustus* event (MP-28), a decrease in cricetid diversity accompanied the appearance of the glirid genus *Miodyromys* and the eomyid *Rhodanomys* [14], which continue beyond the Oligocene–Miocene boundary (Fig. 6). No dramatic faunistic changes are observed across the Oligocene–Miocene boundary. Theriodomyidae and Cricetidae are missing in the latest Oligocene Ebro Basin record, which is characterized by a predominance of Eomyidae and Gliridae. Cricetidae would reappear later during the early Miocene due to new immigrations, whereas Eomyidae and Gliridae continued in diversification. All these late Oligocene faunal changes took place in the setting of the ongoing global changes which resulted in two  $\delta^{18}\text{O}$  maxima of the oceanic record during the early to late Oligocene transition (Oi2a and 2b) and in the punctuated  $\delta^{18}\text{O}$  decrease which characterized most of the late Oligocene until the occurrence of the earliest Miocene Mi1 event [37,39,40,45].

This new magneto–biostratigraphic data set provides a more robust chronology for the Oligocene European biochronological subdivisions [46–47] and enables their more accurate correlation with the standard marine stages (Fig. 6). The diverse European Late Eocene and Oligocene land mammal ages, such as late Headonian (including MP-19/20), Suevian (including MP-21 to MP-25) and Arvernian (including MP-26 to MP-30) can be more precisely correlated with Late Priabonian, Rupelian and Chattian stages, respectively.

The Western Europe and North America Oligocene mammal faunas share scarce taxa, due to the relatively poor faunal paleoarctic exchanges which occurred throughout the Oligocene between both regions [3]. As a consequence the precise correlation between the mammal sequences in both faunistic zones has remained poorly constrained. The currently available results make intercontinental correlations between the biochronological mammal subdivisions in Western Europe [4] and the North American mammal ages [2,3] more feasible. Therefore, it is possible

to correlate the late Eocene reference levels MP-19/20 with the late Chadronian; MP-21 and MP-22 are correlatable to the Orellan; MP-23 and MP-24 would correspond mainly to the Whithneyan, although MP-24 could reach also early Arikareean; MP-25 to MP-30 correlate to the Arikareean Oligocene span, with MP-25 being correlatable with the earlier Arikareean-1, MP-26 to MP-29 with the Arikareean-2, and finally MP-30 and MN-1 (earliest Miocene) with the Arikareean-3 (Fig. 6).

## 8. Concluding remarks

A reliable chronostratigraphy of the Oligocene SE Ebro basin infill has been established on the basis of combined litho-, bio- and magnetostratigraphic cross-correlation of different composite sections. Based upon faunal constraints and on the long distinctive polarity pattern of local magnetozones, the composite magnetostratigraphy for the eastern and western sectors of the southeastern Ebro Basin is correlated unambiguously to the GPTS from chrons C15n to C6Cn.2n, a continuous record in a 1800 m thick succession, lasting about 11.1 million years from the latest Eocene to the earliest Miocene. This correlation of the local polarity magnetic successions to the GPTS has allowed the continuous dating of the stratigraphic successions and of floral and mammal bioevents recorded in the basin. The Rupelian and Chattian ranges are now well-established in the studied non-marine successions, as well as their boundaries with respect to Priabonian and Aquitanian.

This paper provides reliable absolute dates for local mammal biostratigraphic units which are related confidently to the European Oligocene MP (mammal Paleogene) reference levels, resulting in a more appropriate chronological meaning for these biochronological units (Fig. 6). As a consequence the European MP reference levels are more precisely correlated with the marine stages Rupelian (including MP-21 to MP-25) and Chattian (including MP-26 to MP-30). This two-fold subdivision of the MP reference levels corresponds loosely to the European Suevian and Ar-

vernian mammal ages [45]. The results in the SE Ebro basin are also significant to establish the more approximate equivalence between the European MP reference levels and the North American Latest Eocene, Oligocene and earliest Miocene mammal ages (Fig. 6).

Correlation of the local polarity sequences to the GPTS has allowed more precise dating of the floristic and mammal sequence bioevents as recorded in the basin and enabled their accurate correlation to global Late Eocene and Oligocene paleoclimatic events based on oceanic and terrestrial proxies (Fig. 6). Some of these bioevents are very significant and can be recognized in other Iberian and Western European late Eocene–Oligocene records. A late Eocene floristic change indicating a noticeable climatic degradation took place in the Ebro basin around 34 Ma (Chron C13r), corresponding to the most prominent step in the long term change from a non-glaciated to a glaciated Earth [36,40]. The major faunal turnover which affected Eurasia in the early Oligocene (Grande Coupure) developed around Chron 13n and was coeval to the Oi1 isotopic event. A significant faunal change at the upper part of the early Oligocene took place between the top of Chron 12r and the middle part of Chron 10r, maybe related to coeval cooling and isotopic positive shifts events (Oi2). Finally the late Oligocene–earliest Miocene faunal changes developed in a scenario of oceanic  $\delta^{18}\text{O}$  pulsating increase (Oi2a and Oi2b) followed by a pulsating decrease which would finish with the positive  $\delta^{18}\text{O}$  shift Mi1 at the Oligocene–earliest Miocene transition.

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