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A calibrated mammal scale for the Neogene of Western Europe. State of the art

J. Agustí [a,*], L. Cabrera [b], M. Garcés [c], W. Krijgsman [d], O. Oms [e], J.M. Parés [c,f]

[a] *Institut of Paleontology, M. Crusafont, Escola Industrial 23, 08201 Sabadell, Spain*
[b] *Department of Stratigraphy and Palaeontology, Research Group of Geodynamics and Basin Analysis, Campus of Pedralbes, Faculty of Geology, Universitat de Barcelona, E-08028 Barcelona, Spain*
[c] *Serveis Cientifico-Tècnics, Laboratori de Paleomagnetique (UB-CSIC-CIRIT), Institute of Earth Science J. Almera (CSIC), Solé Sabarís s / n, 08028 Barcelona, Spain*
[d] *Paleomagnetic Laboratory Fort Hoffddijk, Budapestlaan 17, 3584 CD Utrecht, Netherlands*
[e] *Universitat Autònoma de Barcelona, Fac. Ciències, Geologia, 08193 Bellaterra, Spain*
[f] *Department of Geological Sciences, University of Michigan, 2534 C.C. Little Building 425 E. University Avenue, Ann Arbor, MI 48109-1063, USA*

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Abstract

A magnetobiostratigraphically calibrated mammal scale for the Neogene of Western Europe is presented in this paper. The Mammal Neogene (MN) units originally proposed by Mein [Report on activity RCMNS-Working groups (1975)] have been re-defined here on the basis of first appearances of selected small and large mammal taxa. The chronology of the lower boundaries of each unit had been established mostly after the significant magnetobiostratigraphic framework developed in the last decade in a number of Spanish basins: Ebro, Calatayud–Daroca, Vallès–Penedès, Teruel, Fortuna, Cabriel and Guadix–Baza. In the case of the early and middle Miocene (particularly, MN 1, MN 2 and MN 3), the authors have also taken into account the magnetobiostratigraphic framework developed in the North Alpine Foreland Basin. Some alternative correlations of the magnetostratigraphic data from this last basin are proposed in order to achieve a higher degree of consistence with the data from the Iberian basins. A quite well established magnetostratigraphic calibration of the MN boundaries can be proposed for most of the Neogene, from Middle Miocene to Late Pliocene. On the other hand, the chronological boundaries of the Early Miocene MN units are still poorly constrained due to: (1) scarcity of well-studied, continuous, thick magnetostratigraphic sections; (2) the difficulty in defining the boundaries of the MN zones for this time-span due to the relative homogeneity and persistence of the fossil rodent faunas and the absence of significant large mammal dispersal events. Some of the troubles which arise with the application of the MN units strengthen the need to take into account the palaeobiogeographical meaning of these units and their real suitability to date and correlate through extensive geographic areas. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Neogene; fossil mammals; Europe; biochronology; biostratigraphy; magnetostratigraphy; dispersal events

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[*] Corresponding author. Tel.: +34-93-726-17-69; fax: +34-93-727-66-41.
E-mail address: agustibj@diba.es (J. Agustí).

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1. Introduction

The so-called Mammal Neogene (MN) biochronological framework was defined in the 1970s (Mein, 1975) as an attempt to systematise the changes of the Neogene fossil mammal palaeofaunas in Western Europe and Eastern Mediterranean. From that time on, the concept of MN units has been a matter of debate with two main positions. On one hand, it is considered that MNs are pure biochronological units, which (by definition) have loosely or non-defined time boundaries (see for instance de Bruijn et al., 1992). On the other hand, it has been proposed that a less loose definition of the MN chronological boundaries is advisable if this MN system has to be used to date the stratigraphic record (Agustí and Moyà-Solà, 1991). This constraining of time would be convenient for instance for the sake of long distance correlations (by means of selected mammal events developed in widespread geographic areas), and to make the working out of new Neogene fossil mammal data bases now in progress meaningful (such as NOW, "Neogene Old World") (Table 1).

The magnetobiostratigraphic frameworks developed in recent years in some of the thicker and more continuous continental Neogene successions of Western Europe (in Spain and the Alpine Molasse) provide a solid foundation in order to calibrate most of the MN boundaries. It is considered here that both the Iberian and the French–Swiss records can be useful in order to establish an updated magnetobiostratigraphical framework for the Neogene mammalian successions in Western Europe. The possibility of establishing unambiguous correlations between most of the main mammalian events (constrained in well-studied, thick and often continuous stratigraphic sequences) and the Geomagnetic Polarity Time Scale (GPTS) constitutes the base to constrain the chronology of the MN units, on the basis of their congruence with the main mammalian First Appearance

Table 1
Age of the Western European MN Units. Boundary sections hold a magnetobiostratigraphically calibrated record of the transition between two MN units

MN unit	Lower boundary age min (max) Ma	Boundary sections	Basin	Reference	Comments
Mm Q1	2.0	Orce[a]	Guadix–Baza	Agustí et al., 1997	
MN 17	2.5	Galera[a]	Guadix–Baza	Garcés et al., 1997a	
MN 16	3.2	Zujar[a]	Guadix–Baza	Oms et al., 1999	
MN 15	4.2	Villalba Alta.	Teruel	Opdyke et al., 1997	
MN 14	4.9	Cabriel	Cabriel	Opdyke et al., 1997	
MN 13	6.8 (7.3)	Chorrico	Fortuna	Garcés et al., 1998	
MN 12	7.5[b]–7.9[c]	Cabriel	Cabriel	Opdyke et al., 1997[c]	reinterpreted[b]
MN 11	8.7	La Gloria	Teruel	Krijgsman et al., 1996	
MN 10	9.7	Can Llobateres	Vallés–Penedés	Garcés et al., 1996	
MN 9	11.1 (11.5)	Montagut[a]	Vallés–Penedés	Garcés et al., 1996	
MN 7/8	12.5 (13.0)	Aragón	Calatayud–Daroca	Krijgsman et al., 1996	
MN 6	13.8	Aragón	Calatayud–Daroca	Krijgsman et al., 1996	
MN 5	16.0	Vargas	Calatayud–Daroca	Daams et al., 1998	
MN 4	16.6 (17.0)	Schwändigraben	North Alpine Foreland	Schlunegger et al., 1996; Kempf et al., 1997	reinterpreted
MN 3	20.0 (22.1)	Gäbris–Sommersberg[a]	North Alpine Foreland	Kempf et al., 1997	
MN 2	20.0 (22.1)	Findreuse[a]	North Alpine Foreland	Burbank et al., 1992; Schlunegger et al., 1996	reinterpreted
MN 1	23.8 (24.1)	Torrente de Cinca	Ebro	Barberá et al., 1994; Agustí et al., 1994	

[a] Refers to sections that only bear the earliest known record of an MN unit.
[b] This paper alternate reinterpretation.
[c] Age of the MN12 lower boundary according to Opdyke et al. (1997).

Data (FADs) associated to each MN unit by Mein (1975) and other authors (Agustí and Moyà-Solà, 1991; de Bruijn et al., 1992).

In the case of the Spanish record, it must be emphasized that the Iberian peninsula acted as a sort of "cul de sac" where most of the dispersal events that affected Western Europe ended. With a number of exceptions restricted to the Messinian (in which a direct Iberia–Africa connection was established), the origins of these dispersal events were located in and around the Near East, or even further in Asia. Therefore, their occurrence in the Iberian peninsula often resulted from a previous route through France and Central Europe. Moreover, the Spanish basins include by far the highest density of small and large mammalian localities in Europe, thus enabling a higher resolution level in the pattern and timing of the mammalian dispersals in this continent. In the last few years, considerable efforts have been devoted to achieve a detailed magnetobiostratigraphic framework in a number of long terrestrial sections and basins, especially in Spain. This has been the case of the Ebro (Barberà et al., 1994; Agustí et al., 1994; Gomis et al., 1997), Calatayud–Daroca (Krijgsman et al., 1996), Vallès–Penedès (Garcés et al., 1996; Agustí et al., 1997), Teruel (Krijgsman et al., 1996; Garcés et al., 1997c; Opdyke et al., 1997), Júcar (Opdyke et al., 1997), Fortuna (Garcés et al., 1998) and Guadix–Baza (Garcés et al., 1996; Oms et al., 1999) basins. At present, the result of these studies enable one to propose an accurate chronology for most of the Neogene times, except for some time intervals in the early Miocene.

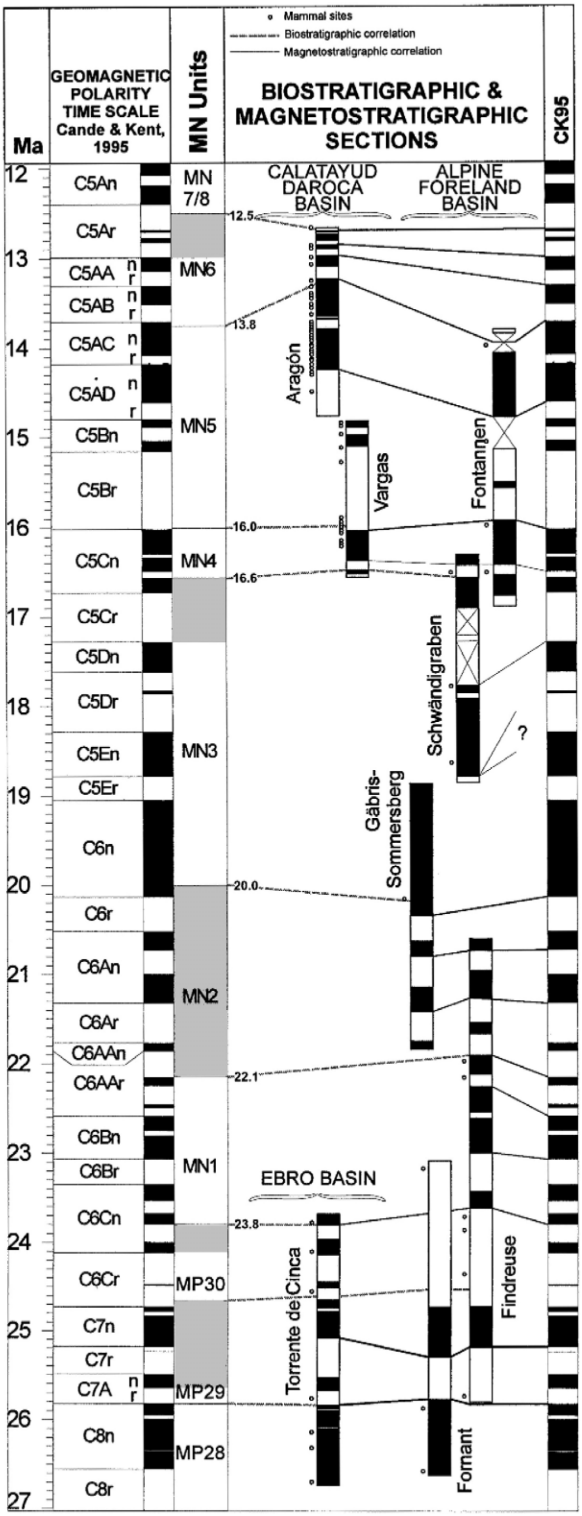
2. Biochronological succession

The MN biochronological system was defined by Mein (1975) on the basis of the first and last appearances of significant taxa and the changes recorded in characteristic evolutionary lineages (mostly rodents). A review and discussion of these criteria is provided in Agustí and Moyà-Solà (1991), de Bruijn et al. (1992) and Agustí (1999). A summary and discussion of these criteria as well as the proposed calibration of the MN boundaries is provided in this section (see Figs. 1 and 2 and Table 2).

2.1. MN 1

The Oligocene–Miocene transition does not record any significant large mammal turnover. Among the small mammals, it is characterised by the persistence of most of the rodent faunas present in the late Oligocene. In order to solve this problem, Agustí and Moyà-Solà (1991) proposed to associate the MN 1 unit with the *Rhodanomys schlosseri* Zone as established on the Ebro Basin. This proposal was founded on the usual lack of large mammals in most of the sections covering the early Miocene and because *Rhodanomys schlosseri* was recorded in several Western and Central European localities. However, this decision created problems, since the previous chronospecies *Rhodanomys transiens* is still present in a number of MN 1 localities, and because the distinction between one or the other chronospecies is difficult for transitional populations (Agustí et al., 1997). An alternate criterion was proposed by Agustí et al. (1997), based on the FAD of the glirid genus *Vasseuromys*. In the Ebro Basin, where the Oligocene–Miocene boundary has been calibrated by magnetostratigraphic correlation (Barberà et al., 1994; Agustí et al., 1994), a primitive species of *Vasseuromys* appears abruptly associated with *R. transiens* in the localities of Ballobar-21 and Costa-Sans (Agustí et al., 1994). This species is also present in other levels of the Western Ebro Basin (*Vasseuromys rugosus* = *Ebromys autolensis* from Bergasa, Autol and Santa Cilia) associated to *R. oscensis* (Cuenca, 1985; Canudo et al., 1994). *Vasseuromys* sp. from the Ebro Basin is not a descendant in situ of other glirids present in the late Oligocene levels of that area (such as *Peridyromys murinus* or *Miodyromys hugueneyae*). Its sudden appearance is therefore considered the result of a dispersal event, as suggested also by the faunal composition of the latest Oligocene faunas in Western Europe.

Accordingly, the base of the MN 1 unit is placed at 23.8 Ma, at the base of chron C6Cn.2n (lower boundary of the *Vasseuromys* Zone in the Ebro Basin). Therefore, the *Vasseuromys* event is almost coincident with the Oligocene–Miocene boundary (the base of the *Vasseuromys* Zone is certainly placed at the top of C6Cn.2n, but it could also be moved to the base of this chron if the presence of *Vasseu-*


Mammal sites
Biostratigraphic correlation
Magnetostratigraphic correlation
Ma
GEOMAGNETIC POLARITY TIME SCALE Cande & Kent, 1995
MN Units
BIOSTRATIGRAPHIC & MAGNETOSTRATIGRAPHIC SECTIONS
CK95
12
13
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17
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23
24
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26
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C5An
C5Ar
C5AA
C5AB
C5AC
C5AD
C5Bn
C5Br
C5Cn
C5Cr
C5Dn
C5Dr
C5En
C5Er
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C6An
C6Ar
C6AAn
C6AAr
C6Bn
C6Br
C6Cn
C6Cr
C7n
C7r
C7A
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C8r
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MN 7/8
MN6
MN5
MN4
MN3
MN2
MN1
MP30
MP29
MP28
12.5
13.8
16.0
16.6
20.0
22.1
23.8
CALATAYUD DAROCA BASIN
ALPINE FORELAND BASIN
EBRO BASIN
Aragón
Vargas
Fontannen
Schwändigraben
Gäbris-Sommersberg
Findreuse
Torrente de Cinca
Fornant
?

romys in the locality of Torrente de Cinca 68 is confirmed). Therefore, according to the definition here proposed, the base of MN 1 is nearly coincident with the base of the Miocene.

The prior magnetostratigraphic calibration of the Haute Savoie Lower Fresh Water Molasse (Burbank et al., 1992), which was subsequently reinterpreted (Schlunegger et al., 1996) on the basis of the updated calibration of the GPTS (Cande and Kent, 1995), yielded different results. The recalibration of the Fornant and Findreuse sections in the Haute Savoie molasse proposed by Schlunegger et al. (1996) yields a younger age for the base of the MN 1. Their preferred correlation assumed a missing normal chron (C6Cn.2n) in the lower part of the Findreuse section due to sampling gaps or depositional hiatuses, and was preferred because it results in smoother accumulation rates. In our opinion these results are not well constrained, since they allow alternate correlations with even smoother accumulation rates under the assumption that relatively short geomagnetic chrons can be missed in the local magnetostratigraphy. An alternate correlation of the Findreuse and Fornant sections (Fig. 1) that misses chrons C7An, C6Cn.1n and C6Cn.3n provides a better match with the GPTS and rules out the apparent faunal diachrony (Fig. 1). Sampling interval in these sections is sufficiently loose to hold these uncertainties. Our conclusion is that the contrasting results of the Alpine Molasse do not provide strong evidence for a diachrony between central Europe and Iberia. It most likely represents a lack of resolution of the magnetostratigraphic record.

2.2. MN 2

With respect to MN 1, this unit is characterized by the FAD of some rare moschoid artiodactyls such as *Andegameryx* and *Amphitragulus* (Agustí and Moyà-Solà, 1991). However, among rodents the distinction can be established only on the basis of particular stages of evolution of cricetids (*Eucricetodon*) and eomyids (*Ritteneria*). The younger part of this unit is characterised by rodent taxocenoses which are dominated by eomyids of the genus *Ligerimys* and by the first Miocene dispersal of *Pseudaelurus*, *Xenohyus* and the first giraffids of the genus *Teruelia* (Moyà-Solà and Agustí, 1990).

Up to now, no well-calibrated sections have been described in the Iberian basins covering this unit, although a number of localities in the Ebro and Loranca basins can be referred to it (Cetina de Aragón, Valquemado; Daams et al., 1987; Morales and Soria, 1984; Morales et al., 1986). The nearest magnetostratigraphic constraint is the youngest MN 1 locality in the Findreuse section (Burbank et al., 1992), which was later correlated to chron C6AAr.2n (Schlunegger et al., 1996) at about 22.4 Ma. As discussed above, the magnetostratigraphy of the Findreuse section allows alternative correlations. An alternate, but not necessarily preferred, correlation for the upper part of the Findreuse section that misses the very short chron C6AAr.2n (Fig. 1) yields a better fit with the GPTS, and a maximum age for the lower MN 2 boundary of 22.1 Ma (C6AAr.1n). In any case, this datum is very badly constrained since no early MN 2 localities have been to date calibrated, and further work will be needed in order to bracket the MN 1/MN 2 boundary with more precision.

2.3. MN 3

In contrast to previous units, MN 3 can be easily recognized and correlated on the basis of the significant overland dispersal which affected the large mammalian communities in Europe following the establishment of the “Gomphothere-bridge” and improved communication with the African continent. A large number of herbivores entered Europe during this time, including equids (*Anchitherium*), anthracotherids (*Brachyodus*), suids (*Aureliachoerus*), cervids (*Procervulus*, *Lagomeryx*, *Acteocemas*),

Fig. 1. Biostratigraphic and magnetostratigraphic correlations across the different Lower to Middle Miocene sections of the Calatayud–Daroca, Ebro and Alpine Foreland Basins. Biostratigraphic (*magnetostratigraphic*) boundary lines correlate towards the time scale on the left (*right*). Shaded time slices in the MN units column represent uncertainties of the MN boundary ages. Crosses in the magnetostratigraphic logs represent significant sampling gaps. Correlation of the Fornant–Findreuse and Schwändigraben–Fontannen sections to the GPTS has been reinterpreted in this paper (see text for explanation).

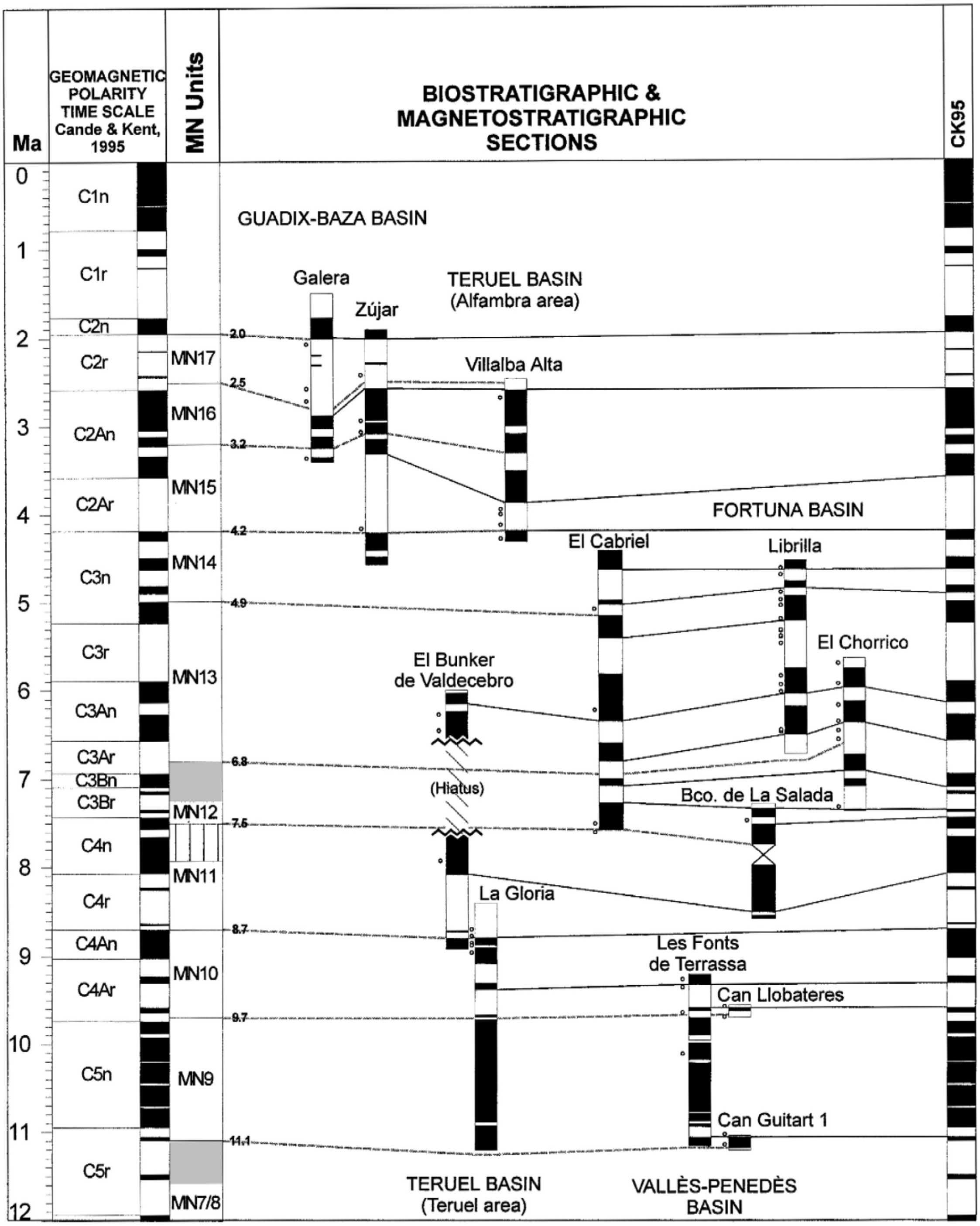

Fig. 2. Biostratigraphic and magnetostratigraphic correlations across the different Upper Miocene and Pliocene sections of the Iberian basins. Stripped rectangle between MN 11 and MN 12 in the MN units log represents the uncertainty of this boundary age due to alternate correlations of the lower part of the Cabriel section (Opdyke et al., 1997), partially reinterpreted in this paper (see Fig. 1 caption for further explanations).

Table 2
FAD of Neogene small and large mammalian taxa used in this paper as a criterion to define the lower boundaries of the MN units

MN unit	First appearances small mammals	First appearances large mammals
MQ 1/ MN 17	*M. ostramosensis Kislangia gusi, M. tornensis Mimomys pliocaenicus, M. reidi*	*Canis, Pachycrocuta, Praeovibos Eucladoceros*
MN 16	*Kislangia ischus Mimomys polonicus, Kislangia cappettai, M. hajnackensis*	*Equus, Mammuthus, Homotherium, Megantereon, Ursus etruscus, Pliohyeana perrieri, Gazellospira torticornis, Arvernoceros ardei, Hesperidoceras merlai, Cervus perrieri*
MN 15	*M. occitanus, Oryctolagus, Mimomys vandemeuleni, M. davakosi*	*Chasmaportetes lunensis*
MN 14	*Promimomys, Trilophomys Celadensia, Castor*	*Sus arvernensis, Croizetoceros, Acinonyx, Felis issiodorensis*
MN 13	*Paraethomys, Rhagapodemnus, Stephanomys, Apodemus, Apocricetus*	*Parabos, Paracamelus, Agriotheirum, Nyctereutes Hexaprotodon*
MN 12	*Parapodemus barbarae, Huerzelerimys turoliensis, Occitanomys adroveri*	*Pliocervus, Hispanodorcas, Palaeoryx, ''Procapreolus''*
MN 11	*Parapodemus lugdunensis, Huerzelerimys vireti, Occitanomys sondaari*	*Birgerbohlinia, Lucentia*
MN 10	*Rotundomys, Pliopetaurista, Schreuderia Progonomys cathalai*	*Hyaenictis almerai, Adcrocuta eximia, Microstonyx major, Tragoportax gaufryi*
MN 9	*Cricetulodon*	*Hippotherium, Decennatherium Machairodus*
MN 7 + 8	*Megacricetodon ibericus, M. gregarius*	*Parachleuastochoerus, Propotamochoerus, Palaeotragus, Protragocerus, Tetralophodon*
MN 6	*Megacricetodon crusafonti, Megacricetodon gersi*	*Tethytragus, Hispanomeryx, Euprox Listriodon*
MN 5	*Megacricetodon collongensis*	*Miotragocerus Micromeryx Heteroprox, Hispanotherium*
MN 4	*Megacricetodon primitivus*	*Bunolistriodon, Dorcatherium, Chalicotherium, Eotragus Prodeinotherium*
MN 3		*Gomphotherium Procervulus, Lagomeryx, Actoocemas Palaeomeryx Brachyodus, Anchitherium, Aureliachoerus, Hemicyon*
MN 2	*Ligerimys, Prolagus, Lagopsis Ritterneria manca*	*Teruelia, Lorancameryx, Oriomeryx, Pseudaelurus, Xenohyus, Andegameryx, Amphitragulus*
MN 1	*Rhodanomys schlosseri, Vasseuromys*	*Hyotherium*

palaeomerycids (*Palaeomeryx*) and proboscideans (Gomphotheridae). Among the carnivores, this unit records the first entry of the ursids with the genus *Hemicyon*. The spread of new herbivore inmigrants into Western Europe resulted in the extinction of most of the previous Ramblian artiodactyls, such as *Xenohyus* and *Teruelia*, whereas *Andegameryx* and *Cainotherium* persisted. Among the small mammals, this unit does not record any significant dispersal and the rodent taxocenosis are still dominated by the eomyids of the genus *Ligerimys* and a variety of glirids. The upper part of this unit is thought to cover the so-called “Cricetum vacuum” in Western Europe (Daams and Freudenthal, 1990), that is, the interval between the last localities with *Eucricetodon* and the first ones with the advanced “Miocene” cricetids of the genus *Megacricetodon*. The peculiar cricetid genus *Melissiodon* is usually present as the only representative of this family, although *Democricetodon* and *Neocometes* can be found in some localities.

Little is known about the calibrated age of the MN 3 faunas from Iberia and, as in the former units, we follow the magnetobiostratigraphic results from the North Alpine Foreland Basin. The oldest MN 3 localities in the Gäbris-Sommersberg and Goldinger sections correlate to the lower part of chron C6n (Kempf et al., 1997), and place the base of the MN 3 unit at a minimum age of 20.0 Ma (Fig. 1). Again, there is currently no precise datum for the MN2/MN 3 boundary, since absolute datings for upper MN 2 localities are not yet available.

2.4. MN 4

There are good records of long distance correlation for the lower boundary of MN 4, since this unit is characterized by a second wave of overland dispersals of large and small mammals: *Prodeinotherium*, *Bunolistriodon*, tragulids (*Dorcatherium*), *Eotragus* and *Megacricetodon*. The dispersal events at this time are mainly of Western Asian origin, and only *Prodeinotherium* can be quoted as an African immigrant at this time. The remaining artiodactyl taxocenosis is basically composed of the same elements as the former mammal unit (cervids included), except for the disappearance of *Acteocemas* and *Andegameryx* (Moyà-Solà and Agustí, 1990; Agustí and Moyà-Solà, 1991).

In the Iberian basins, the MN 3/MN 4 boundary does not have a good age constraint. This boundary is biostratigraphically well bracketed in the Schwändigraben section (Schlunegger et al., 1996; Kempf et al., 1997) in the Napf area (Swiss Alpine Molasse). The magnetostratigraphic data of the Schwändigraben–Fontannen composite sequence is not of very high resolution due to the abundance of unfavourable lithologies in most of the section. Radiometric and biostratigraphic constraints, however, allow a coarse but realistic correlation to the GPTS (Schlunegger et al., 1996). In Fig. 1, we include the new biostratigraphic framework provided for these sections (Kempf et al., 1997), but we have not applied their proposed recalibration of the same sections since these authors have not provided arguments to rule out earlier results (Schlunegger et al., 1996) and their alternate correlation results in a very poor fit with the GPTS. Therefore, we place the lower boundary of the MN 4 unit between chrons C5Cn.2r and C5Cr, between 16.6 Ma (age of the MN 4 locality Eimättili) and 17.2 Ma (age of the youngest MN 3 locality at the Schwändigraben section).

2.5. MN 5

In Central Europe, a distinction between MN 4 and MN 5 can be wisely established on the basis of the FAD of the cricetid *Cricetodon*. The first members of this genus (*Cricetodon versteegi*) are recorded in Anatolian levels assigned to MN 1 (Bruijn and Unay, 1996). In Western Europe, they appear much later, associated with *Megacricetodon collongensis* (for instance, in the localities of Pont-Levoy and Vieux-Collonges). However, in the Central basins of Spain (Calatayud–Daroca, Duero), *Cricetodon* is not recorded in most of the localities with *M. collongensis* (zone D of Daams and Freudenthal, 1981). However, despite the absence of *Cricetodon*, the rodent taxocenosis of the *Megacricetodon collongensis* Zone in Spain are clearly characterized by a shift towards drier conditions. This environmental change can be extended to other parts of Western Europe and covers most of the *Megacricetodon collongensis* Zone. Therefore, despite the regional absence of *Cricetodon*, we extend the lower boundary of MN 5 to cover also the *M. collongensis* faunas from Spain (this implies that there was a delay in the entry of the first *Cricetodon* species in the Iberian peninsula).

The lower boundary of the MN 5 was first placed at 17. 3 Ma (base of chron C6Cr) at the lower boundary of zone D from the Vargas section in the Calatayud–Daroca Basin (Krijgsman et al., 1996). It was later re-evaluated (Daams et al., 1998) on the basis of new biostratigraphic information and a revised correlation between the Vargas and Armantes sections. The new calibration of the Calatayud–Daroca mammal biostratigraphy yields an age of 16.0, base of chron C5Br, for the base of MN5. These results erase the major differences that existed between the Calatayud–Daroca Basin and the North Alpine Foreland Basin, since the oldest dated MN 5 locality in the Alpine Molasse (Kempf et al., 1997) closely correlates to the C5Br/C5Bn boundary when our alternate correlation of the Fontannen section is considered (Fig. 1).

2.6. MN 6

As in other cases of the MN succession, which were founded as “reference-level”, the MN 6 unit was largely based on the locality of Sansan in France. Originally, the most characteristic rodent element at Sansan was said to be the cricetid *Megacricetodon crusafonti*, described from the Spanish locality of Manchones (Baudelot, 1972). However, Aguilar (1980) showed that the *Megacricetodon* population from Sansan belonged in fact to a different species, *M. gersi*, supposed to be a vicarious variant of the Spanish species. Nevertheless, *M. gersi* or a close population was later recognized in Spain in the Duero (García-Moreno, 1988) and Calatayud–Daroca Basins (Daams and Freudenthal, 1981, 1988), in levels below those with *M. crusafonti*. Therefore, as indicated by the large mammals, Sansan and Manchones represented two separated faunal units.

Therefore, an earlier part (MN 6a) of this unit is characterized by the FAD of a second *Megacricetodon* lineage and the replacement of *Bunolistriodon* by *Listriodon*. *Listriodon* was probably an Asian inmigrant which settled in Europe and Africa as a consequence of the MN 6 dispersal event. In addition to *Bunolistriodon*, MN 6a also records the disappearance of typical early–middle Miocene genera such the rhinoceros *Hispanotherium*, the palaeomerycid *Triceromeryx* as well as the artiodactyls *Cainotherium* and *Amphitragulus*. The second subnunit (MN 6b, *Megacricetodon crusafonti* Zone) is characterized by the FAD of *Tethytragus, Hispanomeryx* and *Euprox.*

We place the lower boundary of the MN 6 unit at 13.7 Ma, the base of chron C5ABr, correlated with the lower boundary of zone F in the Aragón section of the Calatayud–Daroca Basin (Krijgsman et al., 1996; Daams et al., 1998) (Fig. 1).

2.7. MN 7 + 8

Originally, Mein (1975) created the MN 7 unit for some localities bearing an intermediate character between the fauna of Sansan and the youngest fissure infillings from the La Grive complex. However, de Bruijn et al. (1992) decided to join MN 7 and 8, since they were unable to recognize such a tripartition of the late Aragonian faunas (MN 6, 7 and 8). However, MN 7-like faunas are present in the Vallès–Penedès Basin in the sections of Sant Quirze and Font del Ferro, characterized by *Cricetodon albanensis, Cricetodon lavocati* and *Fahlbuschia crusafonti*. Sant Quirze records the FAD of the suids *Propotamochoerus* and *Parachleuastochoerus* and the bovid *Protragocerus*. On the other hand, *Heteroprox* and *Tethytragus* are no longer present. A second set of late Aragonian localities in the Vallès–Penedès Basin such as Can Missert, Castell de Barberà and the lower Hostalets levels record the FAD of the cricetid *Hispanomys*, the first giraffids (*Palaeotragus*) and the hyaenids of the genus *Thalassictis*. This fits rather well in the original definition of MN 8 unit (Mein, 1975), as characterized by the entry of *Hispanomys, Palaeotragus, Protragocerus* and *Tetralophodon.* Despite the fact that the characteristic species *Deperetomys hagni* and *Democricetodon freisingensis* are not recorded in the Spanish basins, this unit can be correlated readily in Western Europe on the basis of the last occurrence of *Cricetodon* and the first occurrence of *Hispanomys*.

We place the lower boundary of the MN 7 + 8 unit between chrons C5Ar.1n and C5Ar.3r, that is, between 13 and 12.5 Ma, correlated as the lower boundary of zone G3 of the Calatayud–Daroca Basin (Fig. 1; Krijgsman et al., 1996; Daams et al., 1998).

2.8. MN 9

The *Hippotherium* dispersal is the first and most outstanding event defining the beginning of the late Neogene in Eurasia. However, the entry of this equid did not involve any special change or replacement in the previously existing faunas of the late Aragonian:

the latest Aragonian and earliest Vallesian faunas in the Vallès–Penedès share the same small and large mammal elements, to the point that they are biostratigraphically undistinguishable if *Hippotherium* is not found (Agustí et al., 1997). A second phase within the early Vallesian can be distinguished in the type-area of the Vallesian, the Vallès–Penedès Basin. Among the small mammals, there is a significant change, involving the spread and dominance of the first true cricetines (*Cricetulodon*), which replace the typical persisting Middle Miocene association of *Megacricetodon* (*gersi–crusafonti–ibericus* lineage) and *Fahlbuschia* (*F. crusafonti*; Agustí, 1982). Among the large mammals, there are no significant extinctions, except for the middle sized felids of the genus *Pseudaelurus* (*P. lorteti*, *P. quadridentatus*). In the Western European basins, the slender giraffids of the genus *Palaeotragus* are replaced by the more robust, sivatherine giraffid *Decennatherium*. In general, localities placed within this zone (Can Ponsic, Santiga, Ballestar, Can Llobateres 1) reflect a much more forested and humid character than the earliest Vallesian localities. Tapirs, tragulids (*Dorcatherium*) and hominoids (*Dryopithecus*) are characteristic elements in these associations.

The lower boundary of this unit is defined by the entry of *Hippotherium*, established at 11.1 Ma (chron C5r.1r), in the Vallès–Penedès Basin (Fig. 2; Garcés et al., 1996, 1997b).

2.9. MN 10

A significant decline in rodent diversity (Agustí, 1978, 1982) and bovid turnover (Moyà-Solà, 1983) led Agustí and Moyà-Solà (1990) to identify the existence of an important faunal change at the Early/Late Vallesian boundary called the “Mid Vallesian Crisis”. (MVC). The MVC involved the local or global disappearance of most of the humid faunal elements characterizing the former biozone, such as the suid *Conohyus*, the cervid *Amphiprox*, the moschid *Hispanomeryx*, the bovids *Miotragocerus* and *Protragocerus*, the rhinoceroses *Lartetotherium sansaniense* and *Dicerorhinus steinheimensis*, the large carnivores of the families Nimravidae and Amphicyonidae. Among the rodents, the MVC involved the disappearance of several cricetids and glirids of early or middle Miocene origin (e.g., *Megacricetodon*, *Eumyarion*, *Bransatoglis*, *Myoglis*, *Paraglirulus*, *Eomuscardinus*), flying-squirrels (*Albanensia*, *Miopetaurista*) and beavers (*Chalicomys*, *Euroxenomys*). In Western Europe, the disappearance of these elements coincided with the spread of murids (*Progonomys* sp) which is recorded at Can Llobateres 2.

The lower boundary of this unit has been established in the Vallès–Penedès Basin at 9.7 Ma, in chron C4Ar.3r (Fig. 2; Garcés et al., 1996, 1997b).

2.10. MN 11

In Western Europe (Vallès–Penedès and the Rhone Valley), this unit records the extinction of the hypsodont cricetids *Rotundomys* and *Anomalomys*. Only the genus *Hispanomys* remains from the once highly diversified Miocene cricetid taxocenosis. A number of artiodactyl taxa disappear (e.g., *Schizochoerus*, *Austroportax* and the small cervid *Euprox*) replaced by *Lucentia* and *Birgerbohlinia*.

The lower boundary of MN 11 unit is placed at 8.7 Ma, the upper part of chron C4An, according to the lower boundary of the *Parapodemus lugdunensis* Zone in La Gloria section, Teruel Basin (Krijgsman et al., 1996) (Fig. 2).

2.11. MN 12

This interval records a significant ruminant turnover, with the entry of *Pliocervus*, *Hispanodorcas*, *Palaeoryx*, *Gazella* and *Procapreolus* and the exit (at this level in the type-area) of *Dorcatherium*, *Micromeryx* and *Lucentia*.

The MN 11/MN 12 boundary is biostratigraphically well bracketed at the base of the Cabriel section (Opdyke et al., 1997). The last magnetostratigraphic calibration of the Cabriel section suggests an age for the MN 11/MN 12 boundary as 8.0 Ma (at the base of chron C4n; Opdyke et al., 1997). The correlation of the lower part of the section is, however, debatable. An alternate correlation of the Cabriel section may yield an age of 7.5 Ma, in chron C4n.1 (Fig. 2). This second choice would be in agreement with the presence of MN 11 fauna in chron C4n at the Bunker section, Teruel Basin (Krijgsman et al., 1996; van Dam, 1999).

2.12. MN 13

This interval records a very important turnover involving the exit of some genera of the previous interval (*Parapodemus, Huerzelerimys, Microstonyx* and "*Procapreolus*") and the dispersal and first occurrence of some Asian and African genera, probably in relation to the Messinian Salinity crisis: *Macaca*, *Nyctereutes*, *Hexaprotodon*, *Paracamelus*, *Parabos*, *Paraethomys*, *Blancomys*, *Protatera* and *Calomyscus* (Aguilar et al., 1983, Agustí, 1989, 1990; Agustí and Llenas, 1996; Morales, 1984; Moyà-Solà et al., 1984; Moyà-Solà and Agustí, 1990).

A minimum age for the lower boundary of MN 13 was established in the Fortuna Basin within chron C3Ar, at about 6.8 Ma (Garcés et al., 1998), which is close to that proposed in the Cabriel section (Opdyke et al., 1997). Recent studies in the Fortuna Basin (Garcés et al., in preparation) permit bracketing the MN 12/MN 13 boundary between 6.8 and 7.2 Ma, between chrons C3Ar and C3Br (Fig. 2).

2.13. MN 14

The base of the MN 14 interval is defined according to the lower boundary of the *Paraethomys–Promimomys* Zone (Teruel Basin, Mein et al., 1983). In the Teruel Basin, the levels above those of the *Stephanomys ramblensis* Zone (MN 13) are characterized by the presence of the bizarre microtoid cricetid *Celadensia*. Mein et al. (1983) used this appearance to establish the base of the MN 14. However, an earlier MN 13 occurrence of *Celadensia* has been reported from the level V3 from Baccinello (Rook and Torre, 1995). Therefore, we prefer to use the FAD of *Promimomys* in order to place the lower boundary of MN 14. Among the small mammals, other than the entry of the first arvicolids, the distinction between the MN 13 and MN 14 interval is mainly based on the evolutionary stages of a number of late Miocene persisting lineages: *Apodemus*, *Stephanomys*, *Paraethomys*, *Ruscinomys* and *Apocricetus*. This is why the limit between the MN 13 and the MN 14 units is so difficult to recognize in the case of some localities which have been placed either in the Late Turolian or in the Early Ruscinian (Alcoy, Caravaca). However, this time-interval is characterized by an abrupt turnover of some large mammal lineages. Particularly, the Miocene–Pliocene boundary involved the extinction of a number of suid and rhinocerotid taxa of Middle–Late Miocene origin, such as *Aceratherium* and *Alicornops*.

The best estimate of the MN 14 lower boundary is found in the Cabriel section (Opdyke et al., 1997, 1998), where the Fuente del Viso mammal site is correlated in chron C3n.3r, at 4.9 Ma (Fig. 2). We interprete this as a minimum age for the MN 13/MN 14 boundary, since we believe the Fuente del Viso faunal assemblage should be considered MN 14 and not latest MN 13 as indicated by Opdyke et al. (1997). Biostratigraphic work in progress in the Librilla section (Fortuna Basin), where the Late Miocene to Pliocene stratigraphic interval is very well exposed and dated by means of magnetostratigraphy (Garcés et al., in preparation), may yield more constraints for this boundary.

2.14. MN 15

This interval is characterized by the first entry of the genera *Mimomys* and *Oryctolagus* and the hyaenid *Chasmaportetes lunensis*.

The MN 14/MN 15 boundary is well constrained and correlates to 4.2 Ma, at the C3n/C2Ar transition according to the data from the Alfambra area in the Teruel Basin. (Opdyke et al., 1997; Fig. 2). This is in good agreement with the correlation of the early MN 15 locality of Zújar-6 with the base of chron 2Ar (Oms et al., 1999).

2.15. MN 16

In Western Europe, the change from MN 15 to MN 16 involved a drastic turnover among small mammal associations. Several muroid genera of late Miocene origin disappeared (*Occitanomys*, *Paraethomys*, *Ruscinomys*, *Apocricetus*) and the arvicolids, although sparsely diversified in Western Europe, become numerically dominant throughout Europe. Among the large mammals, a significant entry of large carnivores and ruminants is also evident (Montopoli Faunal Unit). At the end of this interval, the replacement of the last *Hipparion* by *Equus*, takes place, as well as the entry of the first *Mammuthus*.

The boundary between MN 15 and MN 16 units is established at 3.2 Ma, between the chrons C2An.2r and C2An.2n, according to the results in the sections of Galera (MN 15 at Galera 1C; Garcés et al., 1997a) and Zújar (MN 16 at Zújar 10; Oms et al., 1999) in the Guadix–Baza Basin (Fig. 2).

2.16. MN 17

The distinction between late MN 16 and early MN 17 is one of the major problems of the biochronological subdivision of the European terrestrial Pliocene. The sole basis to distinguish both units according to de Bruijn et al. (1992) is the appearance of the cervid genus *Eucladoceros*, which is present only in those localities displaying a well preserved large mammalian record. Agustí and Moyà-Solà (1991) proposed to refer the MN 17 unit to the *Mimomys pliocaenicus–Mimomys reidi* Range Zone. In the Guadix–Baza Basin, the former species is absent, replaced by other endemic taxa (provisionally classified as *Mimomys* cf. *ostramosensis* and *Mimomys* cf. *reidi* in Agustí, 1986). Therefore, we have used the FAD of *Mimomys tornensis* at the level of Galera 1G to correlate the lower boundary of MN 17 in the basin. *Mimomys tornensis* is associated with *Mimomys medasensis* and *Kislangia gusii* in the upper part of the Galera section. Although there is not a significantly large mammal assemblage recorded from this section, this rodent association is very similar to that of the locality of Almenara 1 (= Casablanca 1; Agustí et al., 1993) in Eastern Spain. Almenara-1 has produced an abundantly large mammal association including *Equus stenonis, Canis etruscus, Ursus etruscus, Pachycrocuta brevirostris, Eucladoceros* sp. and Ovibovini indet (Agustí et al., 1987). This association is very similar to that of the Olivola Faunal Unit in Italy and characterized by typical latest Pliocene and even earliest Pleistocene taxa such as *Pachycrocuta brevirostris* and Ovibovini indet. The Almenara 1 association reinforces the assignment of the *Kislangia gusii* Zone to MN 17.

The youngest MN 16 locality in Spain is found at the top of chron C2An in the Villalba Alta section in the Teruel Basin (Opdyke et al., 1997). The oldest MN 17 localities in the sections of Galera (Garcés et al., 1997a) and Zújar (Oms et al., 1999) in the Guadix–Baza Basin, correlate to the lower part of C2r. Therefore, the lower boundary of the MN 17 unit is dated to about 2.5 Ma, close to the C2An/C2r boundary (Fig. 2).

3. Concluding remarks: present state of the art

Some concluding remarks can be presented on the basis of the currently available data on the Western Europe Neogene magnetobiochronology of fossil mammals. These remarks focus on the progress attained during the last 5 years, and summarize our current knowledge to calibrate the Neogene mammal faunaes in Western Europe.

(1) A comprehensive magnetostratigraphic calibration of the MN units can be proposed for most of the Neogene, especially for MN units which range from Middle to Late Pliocene and Pleistocene, thanks to the magnetobiostratigraphic data gathered from sections in Spain. Some of the MN boundaries, however, will be even better constrained, provided that further bio-magnetostratigraphic studies continue in the near future.

(2) Chronological constraining of the boundaries of the Early Miocene MN units is still weakly established due to the scarcity of well-studied, continuous thick magnetostratigraphic sections, and may be revised as new data from suitable sections are added to the existing data set. The integrated magneto and biostratigraphic records in the Alpine Molasse are of great interest for the sake of calibration of these Early Miocene MN units, since they are complementary with the Spanish records. Nevertheless, the use of all of these records has to be made taking into account that some of the proposed correlations are loosely constrained and may need further revision. In the present paper, we have proposed a reinterpretation of some published magnetostratigraphic data from the Haute Savoie region and the Swiss molasse (Burbank et al., 1992; Schlunegger et al., 1996; Kempf et al., 1997). But we remind the reader that these reinterpretations are only alternative correlations. They are preferred only on the basis of a better fit with the GPTS and fewer contradictions with the results from the Iberian basins. Further higher resolution magnetostratigraphic studies in the Alpine region would be required in order to provide conclusive arguments on the chronology of these faunas.

(3) The definition of the boundaries of some of the MN units for some time spans (i.e., Early Miocene) is especially difficult because of the relative homogeneity and persistence of the fossil rodent faunas and the absence of significant large mammal dispersal events with well contrasted validity in wide geographical domains. Moreover, the alternate criteria proposed to face this problem of definition are in some cases far from a general agreement.

(4) In any case, the available biostratigraphic database in diverse European and Western Asian areas suggest the need to take into account the palaeobiogeographical significance of these units and their real suitability to date and correlate over extensive geographic areas.

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