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A new chronology for the middle to late Miocene continental record in Spain

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Abstract

The first detailed chronology for the middle to late Miocene continental record in Spain is presented, based on high-resolution magnetostratigraphic data of mammal-bearing sections which were studied in several basins (Calatayud–Daroca, Teruel, Vallès–Penedès, Duero and Júcar–Cabriel). Our results indicate that these sections compose an almost complete magnetostratigraphic succession from the lower Aragonian (MN4) to the middle Turolian (MN12). Seven successive Mammal Neogene (MN) zone boundaries are directly dated in these sections, which often contain faunas of two successive zones in superposition. The three oldest boundaries are dated in the Aragonian type area (Calatayud–Daroca Basin). The MN4/MN5 boundary (Vargas section) occurs in chron C5Cr(o) with a corresponding age of 17.26 ± 0.01 Ma, the MN5/MN6 boundary (Aragon section) in chron C5ACn(0.8), with an age of 13.75 ± 0.03 Ma, and the MN6/MN7–8 boundary (Aragon section) in the interval C5Ar.1n–C5Ar.3r with an age of 12.75 ± 0.25 Ma. The MN7–8/MN9 (Aragonian/Vallesian) boundary, occurring in chron C5r.1n at 11.1 Ma, and the MN9/MN10 boundary, in chron C4Ar.3r at 9.7 ± 0.1 Ma, are recorded in the Vallès–Penèdes Basin (Vallesian type area) and are supported by the results from the Duero Basin (Torremormojón section). In the Turolian type area (Teruel Basin), the MN10/MN11 (Vallesian/Turolian) boundary (La Gloria section) occurs in chron C4An(y) at 8.7 ± 0.1 Ma. Taking into account the pre-existing data from the Júcar–Cabriel Basin, the MN11/MN12 boundary (Cabriel Valley section) is recalibrated to C4n.1n, at an age of 7.5 ± 0.1 Ma.

Keywords: Spain; biostratigraphy; magnetostratigraphy; mammals; chronology; Miocene

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1. Introduction

The continental biostratigraphic time scale for the European Miocene still lacks a reliable chronological framework. Correlation of Mammal Neogene (MN) zones — with corresponding faunal assemblages and significant bioevents — to the absolute time scale is mainly based on correlation with marine biostratigraphy and regional zonation (e.g. Paratethys Stages) [1]. Radiometric dating of intercalated volcanic sedi-

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ments is rare and nearly always requires extrapolation over a large stratigraphic interval to the position of the fossil locality. Magnetostratigraphy of long, continuous non-marine sequences has been proposed as an alternative to these approaches, but magnetostratigraphic studies of continental deposits are often thought to be hampered by the abundance of hiatuses and (unknown) changes of sedimentation rates and the scarcity of long continuous outcrops. The comparison of continental fossil localities or

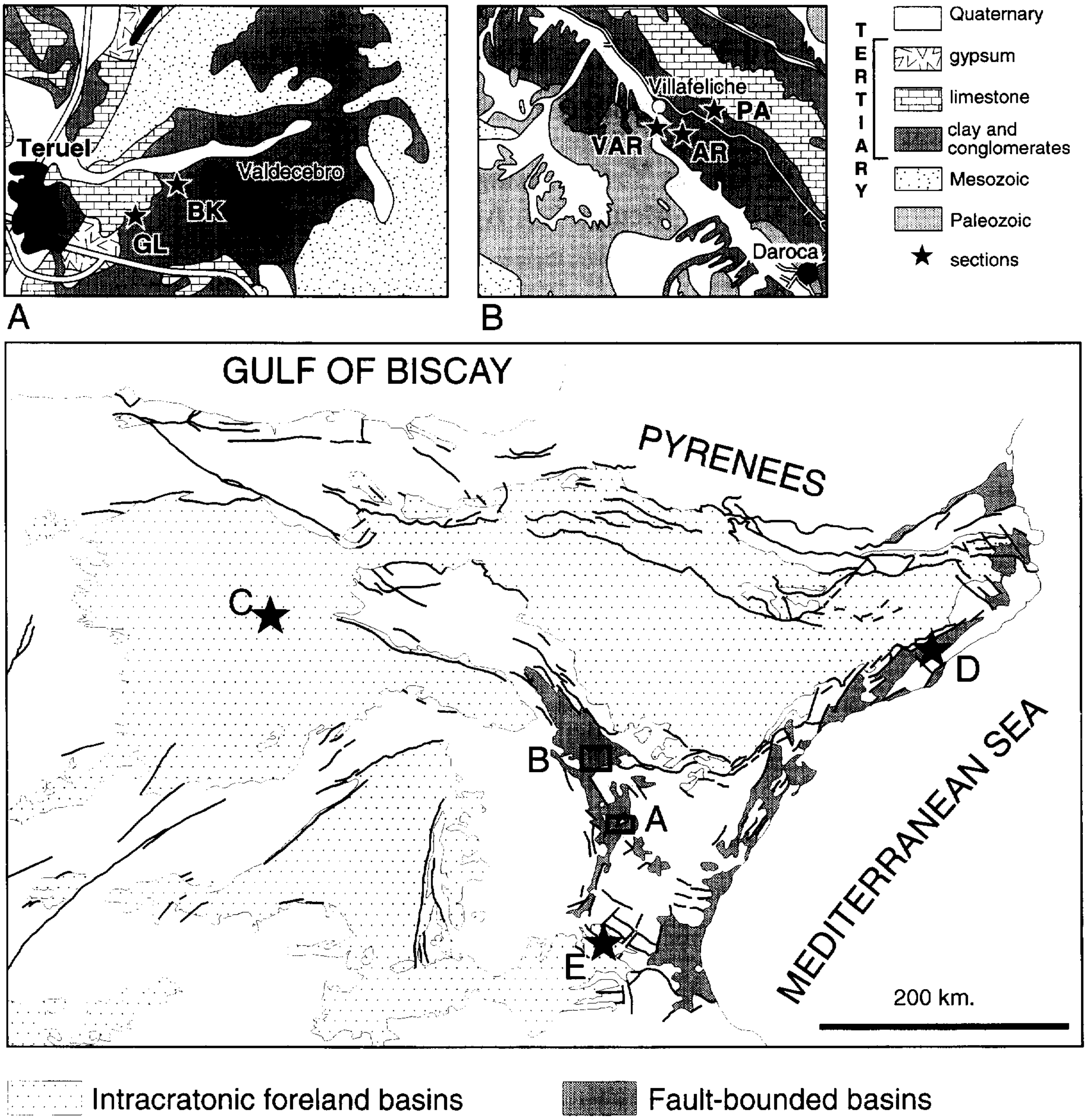


Fig. 1. Location map of the studied basins in Spain; *A* = Teruel basin; *B* = Calatayud–Daroca basin; *C* = Duero basin; *D* = Vallès–Penedès basin; and *E* = Júcar–Cabriel basin. Additional maps showing the detailed locations of the sections in (A) the Calatayud–Daroca basin and (B) the Teruel basin. For location maps of the Torremormojón section in the Duero basin see [22,26]; for the Vallès–Penedès basin [5,6]; for the Cabriel Valley section see [2].

regional continental zonations and the marine time scale remains ambiguous if there are no reliable age determinations. It follows that ages of Continental Stage and MN zone boundaries should preferably be determined in single sections which comprise as many as possible fossil-mammal faunas in superposition. For the European Miocene, direct magnetostratigraphic dating of such Stage boundary sections have recently been established in Spain [2–6].

In this paper, we present the magnetostratigraphic results of our middle to late Miocene sections from Spain and their correlation to the geomagnetic polarity time scale (GPTS). On this basis, we establish a detailed biochronology for the middle to late Miocene continental record in Spain. A well-dated chronostratigraphic framework for the continental biostratigraphy allows correlation to the marine biostratigraphy and the stable isotope records. Furthermore, paleoclimatological and paleoenvironmental changes on land can be compared to those from the marine realm. In earlier studies, the Aragonian faunal record showed an important climatic change to a cooler and more humid climate during the middle Miocene MN5 zone [7]. Magnetostratigraphic dating indicated this cooling event to occur at 14.1 Ma [4], and correlation to the marine record showed a time-equivalent increase in $\delta^{18}O$ [8]. Accurate and high-resolution dating thus provides evidence for (global) climatic events.

2. Geological setting and research strategy

Thick non-marine (alluvial and lacustrine) Miocene sequences in Spain were deposited as a consequence of the tectonic evolution of the Iberian plate [9,10], which resulted in a variety of tectonic settings (i.e., extensional half-grabens, compressional and strike-slip fault bounded basins, and foreland peripheral basins linked to the major thrust-fold belts). Some of these tectonically influenced, thick basin infills include stratigraphic sequences which fit quite well the conditions necessary to carry out high-resolution paleomagnetic studies.

To establish a high-resolution magneto-biochronology for the middle to late Miocene, the Calatayud–Daroca and Teruel basins of central Spain (Fig. 1) are among the most favourable areas because of their detailed fossil record and their long, continuous sections. These basins comprise the type localities of the Ramblian [11], the Aragonian [12] and the Turolian [13,14]. An earlier magnetostratigraphic study provided a reliable magnetostratigraphic framework for the Aragonian [4]. We selected several suitable sections for a new, complementary mag-

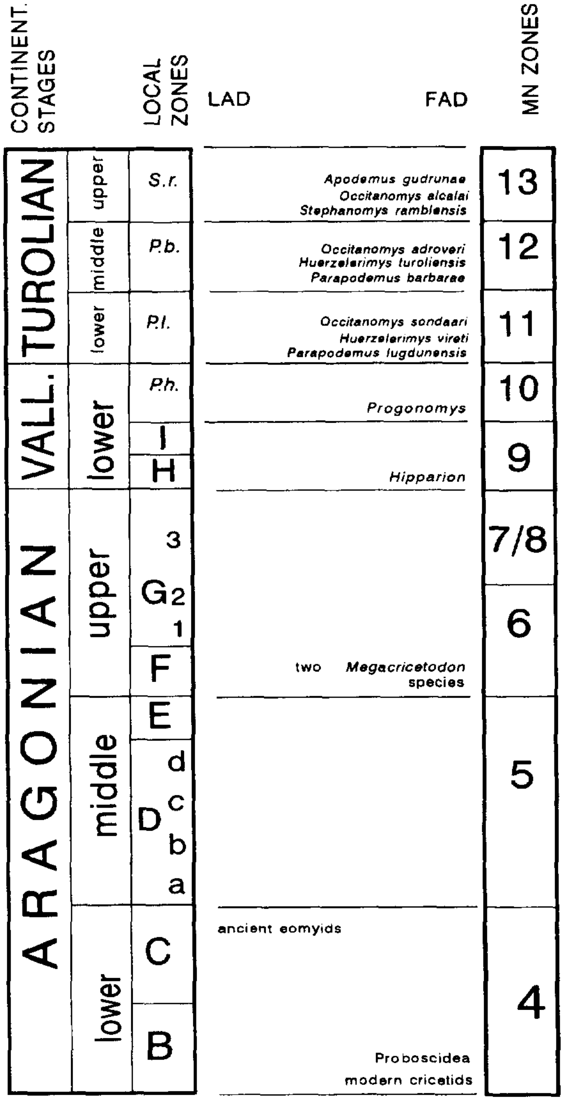


Fig. 2. Correlation between local zones of the Calatayud–Daroca and Teruel basin and the standard MN zonation [15]. *P.h.* = *Progonomys hispanicus*; *P.l.* = *Parapodemus lugdunensis*; *P.b.* = *Parapodemus barbarae*; *S.r.* = *Stephanomys ramblensis*. *LAD* = last appearance datum; *FAD* = first appearance datum.

netostratigraphic study and we added biostratigraphic sampling where necessary.

The biochronology we use is after De Bruijn et al. [15] with the exception that we follow the decision reached in Salzburg (March, 1995) to extend unit MN5 downwards to include former subunit MN4b (as in [16]). Biostratigraphic results indicate that our sections in the Calatayud–Daroca and Teruel basins range from the early to late Aragonian and from the late Vallesian to upper Turolian (Fig. 2). In these basins, the lower Vallesian is mainly represented by isolated localities and suitable continuous sections are not found. Late Aragonian and Vallesian faunal assemblages in a continuous stratigraphic succession are known from the Vallès–Penedès Basin (northeast Spain), the type area of the Vallesian [17], and from the Duero Basin (west Spain) [18,19]. For establishing the chronology of the Vallesian, we incorporated the magnetostratigraphic and biostratigraphic results from sections in the western Vallès area (Vallès–Penedès half-graben) [5,6] and carried out a magnetostratigraphic study on the Torremormojón section (Duero foreland basin). Both the Aragonian/Vallesian and the lower to upper Vallesian boundaries are present in these sections.

To complete the upper part of the stratigraphic range of late Miocene sequences, a previous magnetostratigraphic study in central Spain by Opdyke et

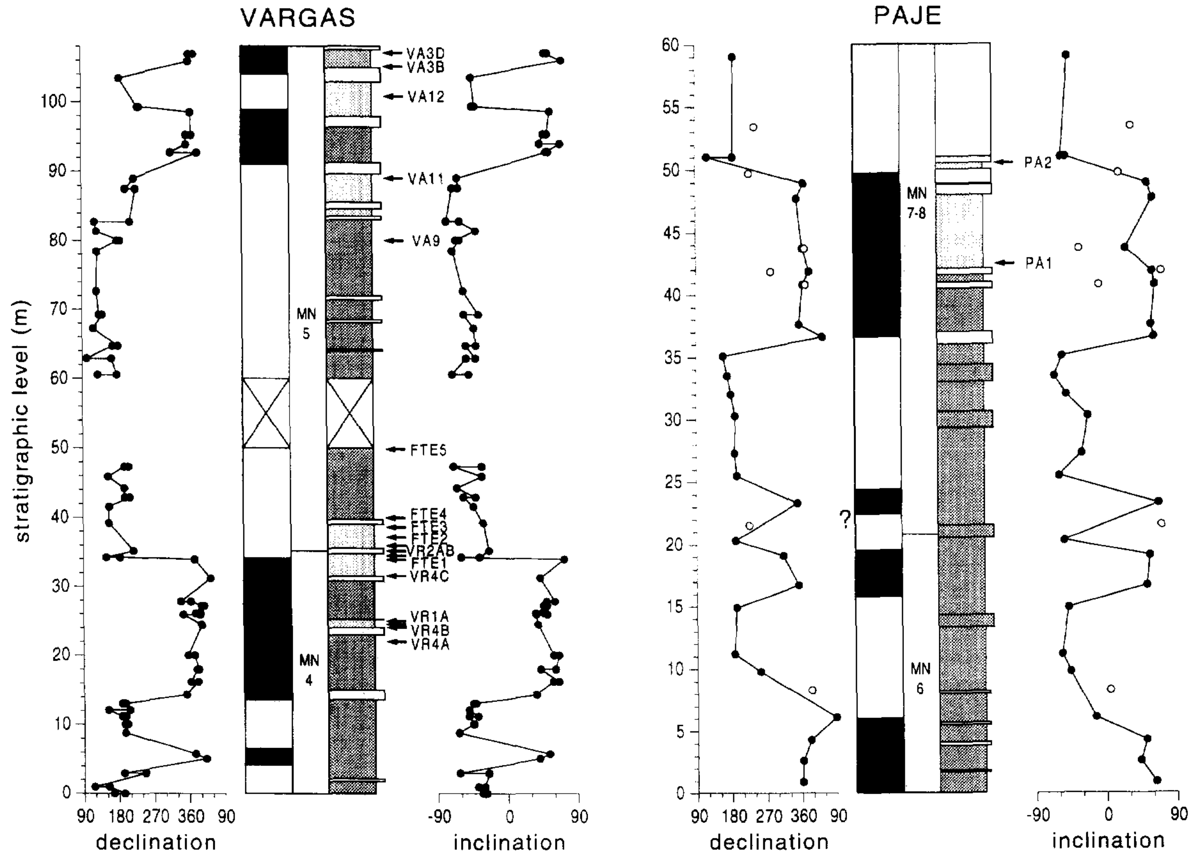


Fig. 3. Polarity zones, MN zonation and lithology of the Vargas and Paje sections (Calatayud–Daroca basin). Arrows indicate positions of fossil localities. *VR* = Vargas; *FTE* = Fuente Sierra, plus some other material; *VA* = Valdemoros; *PA* = Paje. In the polarity column, black = normal polarity interval; white = reversed polarity interval; filled symbols = reliable directions; open symbols = unreliable directions. The MN4/MN5 boundary is determined between localities FTE1 and FTE2. The MN6/MN7-8 boundary is after the Aragon section [4]. The lithology column displays variations of reddish and multi-coloured silts and marls (dark shading), greyish marls (shaded) and limestones (white).

al. [2] on the late Turolian Cabriel Valley section (Júcar–Cabriel Basin) is also incorporated into the final chronology.

3. New sections and sampling

Earlier biostratigraphic and magnetostratigraphic work on the middle to late Miocene sequences in Spain provided a chronological framework for a large part of the Aragonian (middle Miocene) [4] and, recently, also for the Vallesian (late Miocene) [5,6]. To complete these earlier contributions and to extend our chronology to most of the middle and late Miocene, it was necessary to study new sections in the Calatayud–Daroca (Vargas and Paje sections), Teruel (La Gloria section) and Duero (Torremormojón section) basins (Fig. 1).

The Aragonian type area is located in the Calatayud–Daroca Basin of central Spain near the village of Villafeliche [12]. An earlier study showed reliable paleomagnetic results for the Armantes and Aragon sections, which range biostratigraphically from MN5 (former MN4b) to MN7-8 [4]. The new MN4/MN5 boundary is determined in the Vargas section (Fig. 3), situated approximately 500 m west of the Aragon section (Fig. 1). The Vargas section consists of the same type of sediments as in the Aragon section: red and multi-coloured silts and clays and greyish–white marly limestones, which were deposited in distal alluvial and palustrine–lacustrine paleoenvironments.

The magnetostratigraphic results for the top of the Aragon section were hampered by the scarcity of suitable lithologies [4]. The Paje section (Fig. 1; 500 m to the NE) is equivalent to the upper part of the Aragon section. Reddish silts, which were earlier shown to have good paleomagnetic properties, are continuously exposed and reach higher levels than in the Aragon section. The reddish fluviatile and lacustrine sediments in the Paje section are capped by a thick formation of alternating white–grey marls and white lacustrine limestones (Fig. 3). Two new fossil localities (MN7–8) are present in the limestone unit at a higher stratigraphic position than the youngest locality in the Aragon section.

The Torremormojón section, located in the Duero Basin (Fig. 1), comprises a biostratigraphic succession ranging from late Aragonian (MN7–8) to late Vallesian (MN10) and incorporates the MN7–8/MN9 (Aragonian/Vallesian) boundary and the MN9/MN10 boundary [20]. This study is complementary to those of the Vallesian sequences in the Vallès–Penedès Basin [5,6]. Earlier studies in Torremormojón investigated micromammals [21–23], pollen [24], gastropods, ostracods and foraminifera [25]. The lower part of the Torremormojón section (0–18 m) predominantly consists of ochre-coloured detrital sediments (clays and silts) alternating with white–grey marls and limestones (Fig. 4). In the upper part of the section, white limestones dominate and ochre-coloured sediments are rare. The approximately 60 m thick section comprises seven well-de-

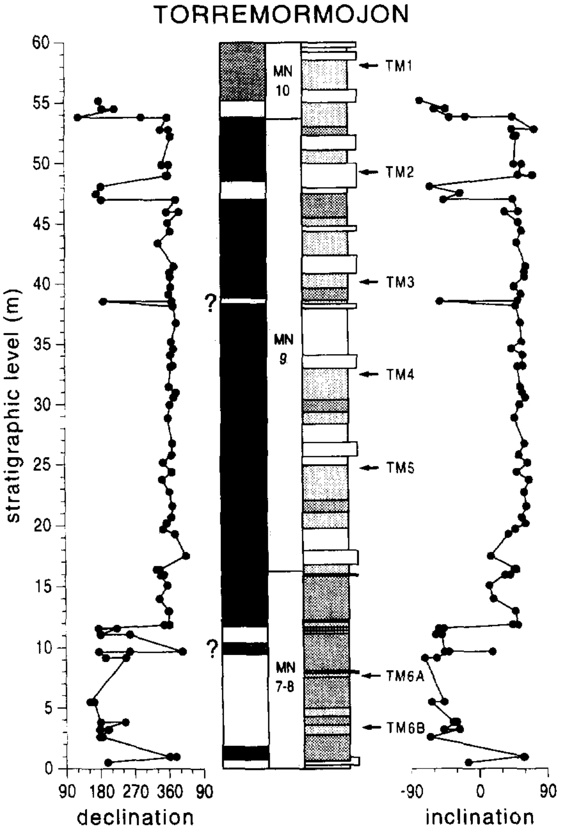


Fig. 4. Polarity zones, MN zonation and lithology of the Torremormojón (Duero basin, along the road C612 between Medina de Rioseco and Palencia) section. TM = Torremormojón. The MN7–8/MN9 boundary is determined between localities TM6a and TM5, the MN9/MN10 boundary between TM2 ans TM1. See also caption to Fig. 3.

scribed fossil localities which are mainly found in dark-grey marls with abundant gastropods (Fig. 4) [23].

The type area of the Turolian is the Los Mansuetos area (Teruel Basin), located east of the town of Teruel (Fig. 1; [13,14]). The La Gloria and El Bunker sections (Fig. 5) mainly consist of red silty clays with intercalations of red sands, conglomerates (channel fills) and white lacustrine limestones. The regular alternation of dark red silty clays with lighter-coloured, more calcareous silts, similar to that observed in the Armantes section [26], suggests a relation with astronomically induced cyclic climate changes. In the upper part of the La Gloria section (63–72 m), a relatively thick limestone unit is present, which appeared to be favourable for fossil preservation and contain several levels with micromammal assemblages (Fig. 5). This limestone unit can be followed — although its thickness largely decreases — into basal part of the El Bunker section (3–5 m). The Vallesian/Turolian boundary is located between localities AG5b and AG7. The El Bunker section is sampled to higher stratigraphic levels which contain MN11 and MN13 localities (Fig. 5).

The magnetostratigraphic samples were taken by drilling oriented paleomagnetic cores with an electric drill and a generator as power supply, using water as a coolant. Considerable efforts were taken to remove the weathered surface and to sample in sediments as fresh as possible. If the lithology was unsuitable for drilling with water, we took standard oriented hand samples which were drilled with compressed air in the laboratory.

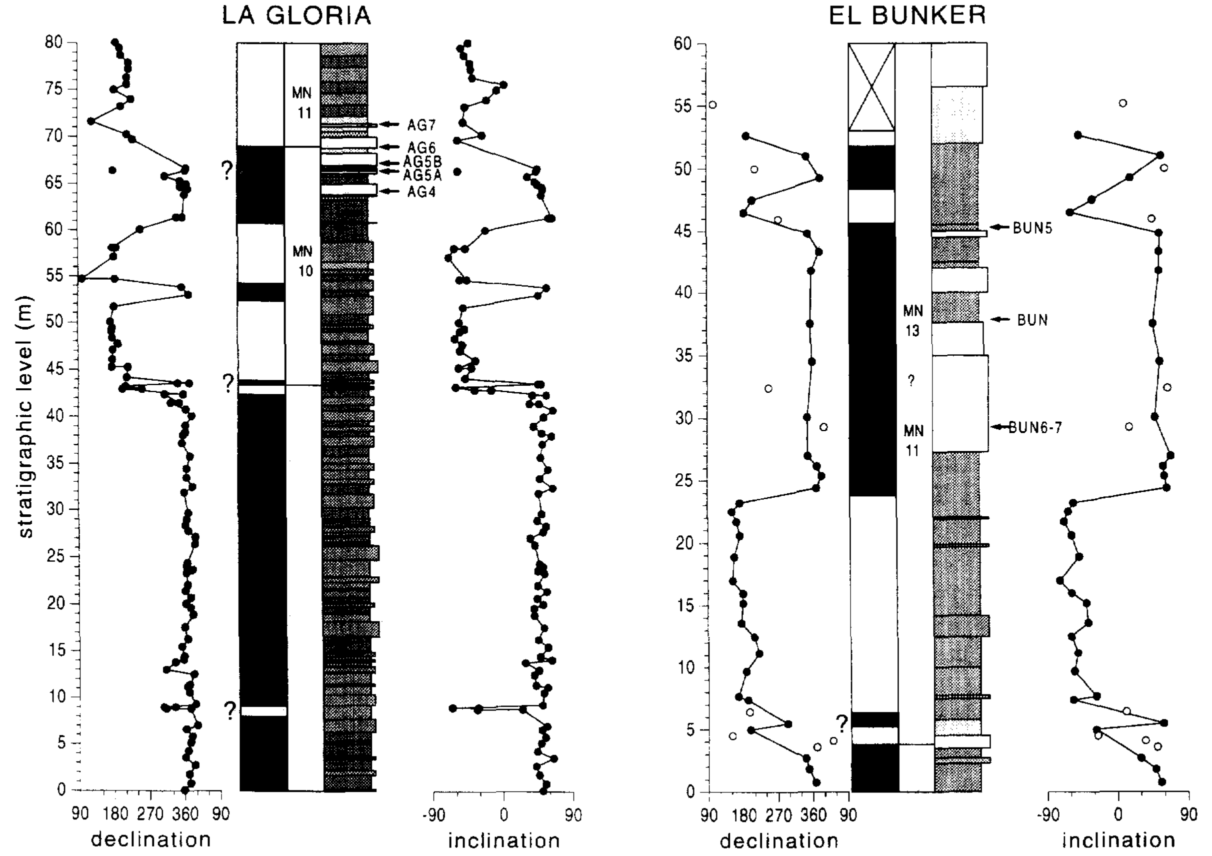


Fig. 5. Polarity zones, MN zonation and lithology of the La Gloria and El Bunker sections (Teruel basin). AG = Los Aguanaces, BUN = El Bunker. The MN10/MN11 boundary is determined between fossil localities AG5b and AG7. See also captions to Fig. 3 and Fig. 4.

4. Paleomagnetic results

At least one specimen per sampling level was progressively demagnetised by applying stepwise heating with small (40°C) temperature increments in a laboratory built, shielded furnace. The thermal demagnetisation process was initiated by heating the samples to 100°C to remove a randomly directed viscous component which has previously been shown to be present in the continental sediments of central Spain [4]. After each temperature step, the natural remanent magnetisation (NRM) was measured on a 2G Enterprises DC SQUID cryogenic magnetometer. Furthermore, we performed some rock magnetic analyses on selected samples from the Torremormojón and Gloria sections to identify the carriers of the NRM components. These experiments include acquisition of an isothermal remanent magnetisation (IRM) on a PM 4 pulse magnetiser and subsequent thermal demagnetisation of this IRM. Low field susceptibilities were measured after each temperature step on a Kappabridge KLY-2.

The widely varying lithologies in the sections nearly all give good paleomagnetic results. The silts

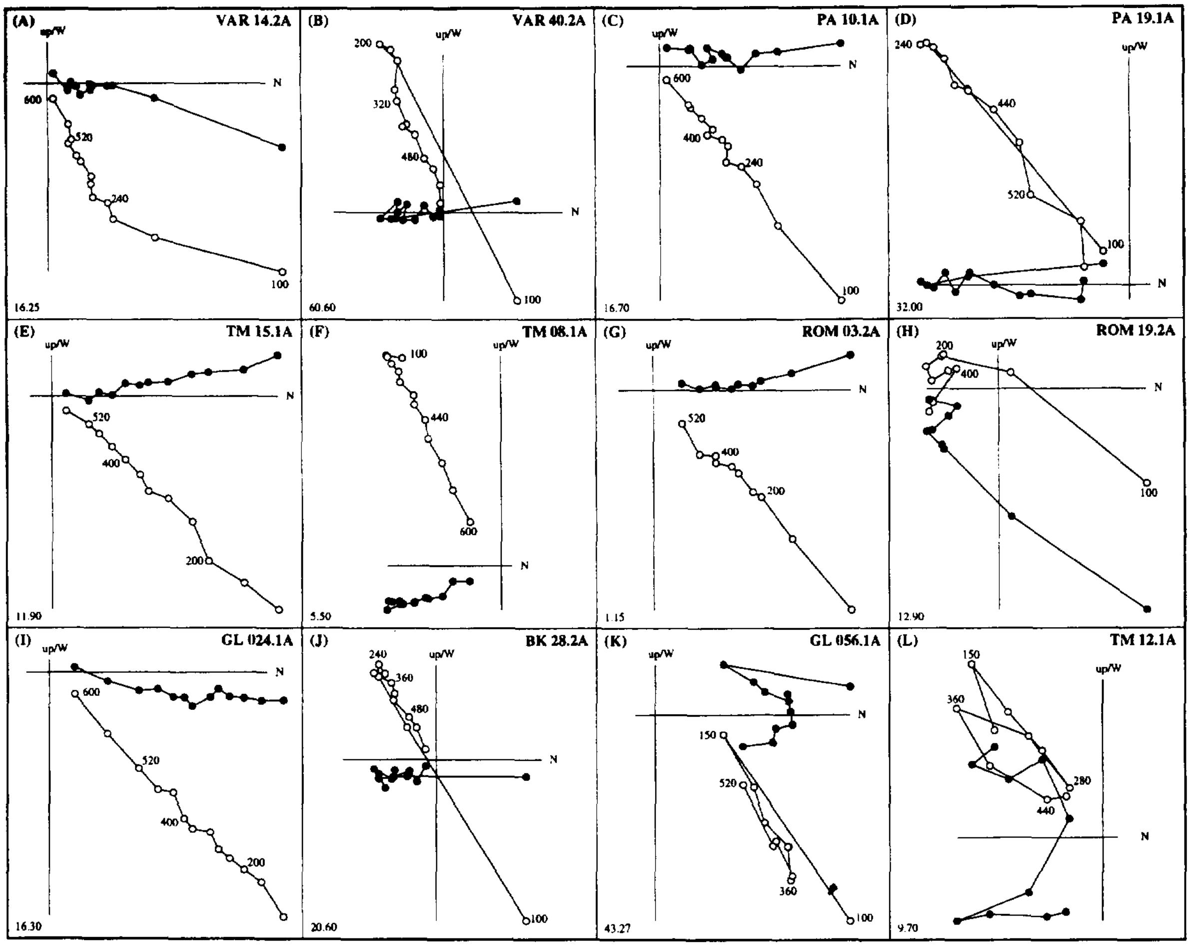
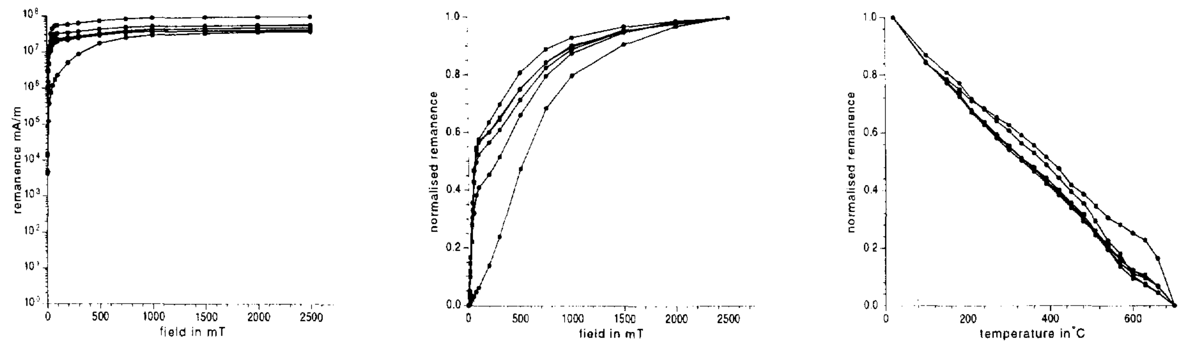


Fig. 6. Thermal demagnetisation diagrams for samples from the new sections studied in the Calatayud–Daroca, Teruel and Duero basins. Filled symbols = the projection of the vector end-points on the horizontal plane; open symbols = projection of the vector end-points on the vertical plane; values represent temperatures in °C; stratigraphic levels are in the lower left-hand corner. (K) and (L) are examples showing demagnetisation of two components between temperatures of 150°C and 600°C. We believe that, in these cases, an early diagenetic component partly overprints the earlier acquired component.

and clays show relatively high characteristic remanent magnetisation (ChRM) intensities (0.1–10 A/m) and initial susceptibilities ($50-1000 \times 10^{-6}$ SI). Demagnetisation diagrams are of good quality and reveal stable ChRM components which show a linear decay to the origin during thermal demagnetisation (Fig. 6). A secondary normal present-day field component was totally removed at 200–240°C, the ChRM component was usually largely removed at 600°C, although in most samples some magnetic component remained up to temperatures of 680°C. IRM acquisition and subsequent demagnetisation indicate that hematite and magnetite are the dominant carriers of the magnetisation, but goethite is often also present (Fig. 7). The whitish limestones show much lower ChRM intensities (0.01–0.1 A/m) and susceptibilities ($0-100 \times 10^{-6}$ SI). Demagnetisation diagrams are difficult to interpret and, in some cases, it was even not possible to determine the polarity.

Both normal and reversed components are revealed in all sections, which demonstrates the primary origin of the magnetic components. At the intervals of the section in which the polarity changes, some specimens show a more complex thermal behaviour. Between temperatures of 240°C and 600°C, these samples show both a normal and a reversed component (Fig. 5k,l). We believe that, in these cases, early diagenetic processes — as observed in the Siwalik red beds [27] — cause a delayed acquisition and a (partial) overprint of the original (earlier acquired) component. Hence, the direction of the following (younger) polarity interval will overprint

(A) LA GLORIA IRM Acquisition IRM Demagnetisation



(B) TORREMORMOJON

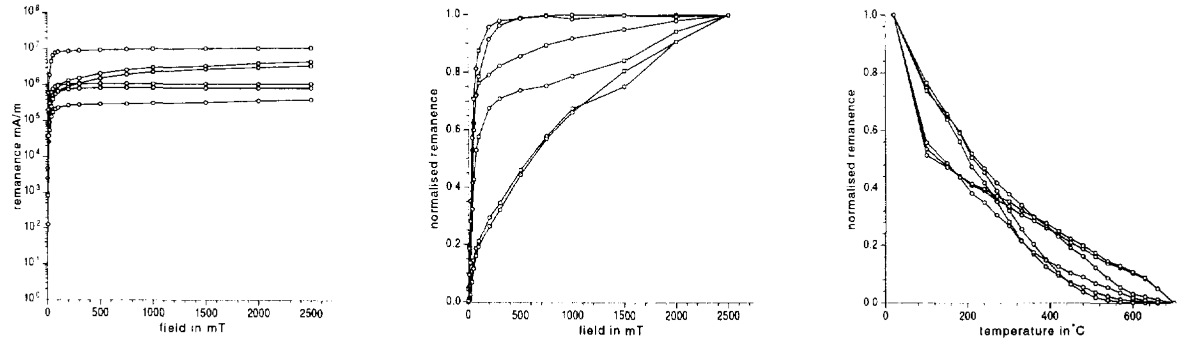


Fig. 7. Examples of IRM acquisition (absolute and normalised values) of samples of (A) the La Gloria and (B) the Torremormojón sections. The initial steep rise (< 200 mT) points to magnetite, the gradual increase at high fields (> 200 mT) suggests the additional presence of hematite. Stepwise thermal demagnetisation of the normalised IRM also show the presence of both magnetite (580°C) and hematite (680°C).

the original direction of the level studied. Diagenetic processes might also cause an overprint of the smallest subchrons and cryptochrons.

5. Correlation to the GPTS

The new data resulting from this work, together with those from earlier contributions [2–6], allow the correlation of the polarity sequences of all sections studied to CK95, the GPTS of Cande and Kent [28]. Some of the previous correlations are confirmed or refined.

The magnetostratigraphic results from the Armantes and Aragon sections showed unambiguous correlations to CK95 (Fig. 8) [4]. The top of the Vargas section is biostratigraphically correlated with fossil locality AM 1 of the Armantes section. Hence, the upper two normal polarity intervals of the Vargas section correlate to chrons C5Cn.2n and C5Cn.3n. The large normal polarity interval in the lower part of the section correlates to chron C5Dn (Fig. 8). The small normal polarity interval, represented by only two levels, most likely corresponds to the so-called cryptochron C5Dr-1, also recorded in CK95. The MN4/MN5 boundary is determined in the reversed interval C5Cr (Table 1). The successive two MN zone boundaries are determined in the Aragon section; MN5/MN6 at C5ACn(0.8) and MN6/MN7–8 in the interval C5Ar.1n–C5Ar.3n. The position of the MN5/MN6 boundary slightly differs from in our earlier work: it is now more precisely determined between localities LUM 20 and LUM 21 [4].

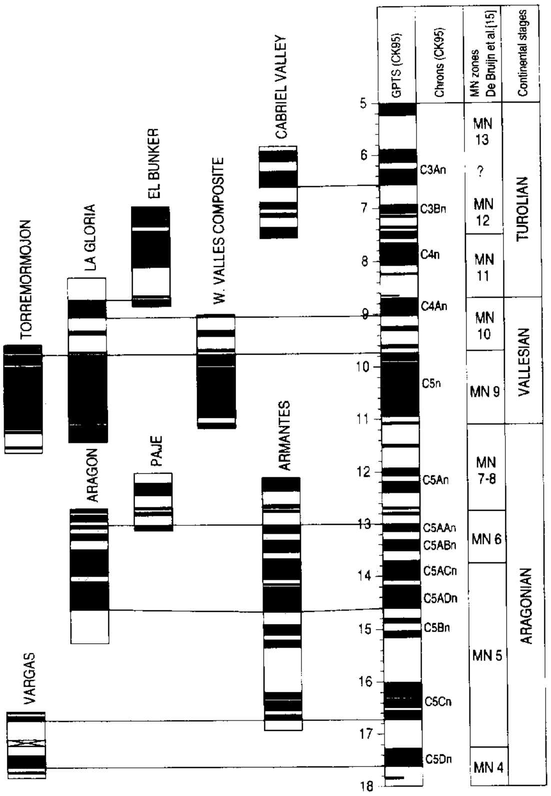


Fig. 8. Correlation of the polarity sequences of the Spanish sections to the GPTS of Cande and Kent [28]. Lines connect corresponding reversal boundaries. Right-hand columns display mammalian zones and stages. Ages of the zone and stage boundaries are from this study (Table 1).

The Paje section is time-equivalent to the top of the Aragon section and the fossil localities Paje 1 and 2 are biostratigraphically younger than LP5H, the youngest fossil locality of the Aragon section [4]. The most likely correlation to CK95 is that the normal polarity interval at the base of the section

Table 1
Positions (or ranges) in the boundary sections of MN zone boundaries and their ages with respect to the GPTS [28]

Zone boundary	Basin	Section	Chron (CK95)	Age (Ma)
MN11/MN12	Júcar–Cabriel	Cabriel Valley	C4n.1n	7.5 ± 0.1
MN10/MN11	Teruel	La Gloria	C4An(y)	8.7 ± 0.1
MN9/MN10	Vallès–Penedès	Montagut	C4Ar.3r	9.7 ± 0.1
MN7–8/MN9	Vallès–Penedès	Montagut	C5r.1n	11.1
MN6/MN7–8	Calatayud–Daroca	Aragon	C5Ar.1n–C5Ar.3r	12.75 ± 0.25
MN5/MN6	Calatayud–Daroca	Aragon	C5ACn(0.8)	13.75 ± 0.03
MN4/MN5	Calatayud–Daroca	Vargas	C5Cr(o)	17.26 ± 0.01

Decimal fraction denotes position within a (sub)chron, as taken from the younger end.

corresponds to chron C5AAn and that the normal polarity interval at the top of the section corresponds to chron C5An.2n (Fig. 8).

The upper alluvial successions in the Les Fonts–Montagut sections (Vallès–Penedès half graben) record a complete sequence of Vallesian mammal assemblages. Ages of MN9 and MN10 units are based on biostratigraphic and magnetostratigraphic correlation of four composite sections showing stratigraphic superposition of biozones [5,6]. The observed reversal pattern allows an unambiguous correlation to the GPTS, mainly based on the presence of the long distinctive normal chron C5n. The MN7–8/MN9 and MN9/MN10 boundaries are determined in chrons C5r.1n and C4Ar.3r, respectively.

The major part of the Torremormojón section (Duero Basin) shows predominantly normal polarities, which suggests a correlation to the long normal chron C5n.2n. The lowermost two short normal polarity intervals might then correlate to C5r.1n and C5r.2n (Fig. 8). One level in the long normal part of the section shows a reversed polarity. This level probably corresponds to a cryptochron of chron C5n.2n; assuming a constant sedimentation rate, the most likely one is C5n.2n-1. No other cryptochrons are recorded, probably because of a low sampling density. Our correlation of the Torremormojón polarity sequence to CK95 indicates a duration of 2 Myr and a sample resolution of approximately 30 kyr. Since the duration of all these cryptochrons is shorter than 20 kyr, it is not surprising that they are not all recognised in our magnetostratigraphy. The MN7–8/MN9 (Aragonian/Vallesian) boundary is located between C5r.2r (TM 6a) and C5n.2n (TM 5). The MN9/MN10 boundary is determined between C5n.1n (TM 2) and C4Ar.2n (TM 1).

The La Gloria section (Teruel Basin) also contains a long interval of normal polarity which can be correlated with chron C5n.2n (Fig. 8). The uppermost normal interval then most likely corresponds to C4An, which implies that chron C4Ar.1n was probably missed under our density of magnetostratigraphic samples. This correlation indicates a duration of 2.4 Myr and a sample resolution of approximately 24 kyr for the La Gloria section. A possible cryptochron is recorded in the lower part of the section (chron C5n.2n). The polarity intervals correlative to the subchrons C4Ar.2n and C5n.1n are partly or totally overprinted by a later, oppositely directed, magnetic component. The MN10/MN11 (Vallesian/Turolian) boundary occurs between localities AG5b and AG7 and is therefore placed in CK95, at the top of chron C4An.

The limestone unit of the La Gloria section can be followed in the field towards the basal part of the El Bunker section. Hence, the normal polarity base of the El Bunker section correlates to C4An, and the second normal interval most probably to C4n.2n (Fig. 8). This correlation indicates that the MN11 zone is extended to the lower part of chron C4n.2n. The results from the upper part of the section are difficult to interpret, probably because of large changes in sedimentation rate and major hiatuses, which are suggested by the observation of MN13 faunas at the upper part of the section and the absence of MN12 localities in the area.

A previous magnetostratigraphic study in Central Spain by Opdyke et al. [2] concerns the late Turolian Cabriel Valley section (Júcar–Cabriel Basin) with the MN12 fossil locality Fuente Podrida [29] at the base. Furthermore, the MN11 locality Balneario is located 300 m to the east and estimated to be roughly 10 m stratigraphically lower [2]. Even if ambiguous, it gives a constraint for the position of the MN11/MN12 boundary. Because this MN boundary is not defined in our sections, we incorporate the magnetostratigraphic results of the Cabriel Valley section and recalibrate the polarity pattern to CK95 (Fig. 8), whereas the former calibration was to the GPTS of Berggren et al. [30]. Our new correlation of the MN11/MN12 boundary is to chron C4n.1n.

6. Chronology

The new magnetostratigraphic data presented in this paper and those available from earlier [2,4] and more recent [5,6] contributions enable the establishment of a chronological framework for the middle to late Miocene, non-marine record in Spain.

6.1. Aragonian (MN4–MN7–8)

The base of the Aragonian (MN3/MN4) is defined by the first appearance of the cricetid

Democricetodon in central and western Europe [11]. The oldest MN zone boundary found in our sections is the recently revised MN4/MN5 boundary, documented in the Vargas section and correlated to chron C5Cr. Our correlation results in an age of 17.26 ± 0.01 Ma, which is so far the only date on this newly defined boundary. The previous magnetostratigraphic dating of the MN4/MN5 boundary in the Aragon section, resulting in an age of 14.1 Ma, was based on the older biostratigraphic definition [4]. The time-equivalent onset of a global mid-Miocene cooling event at 14.1 Ma should now be placed in the upper part of zone MN5.

For the MN5/MN6 boundary, by definition the middle/late Aragonian and Orleanian/Astaracian boundary [31], no new magnetostratigraphic data are obtained. The earlier results from the Aragon section [4] show that the MN5/MN6 boundary is located in chron C5ACn with a corresponding age of 13.75 ± 0.03 Ma. Also for the MN6/MN7–8 boundary, we incorporate the results from the Aragon section, which show that the boundary occurs somewhere in the interval C5Ar.1n–C5Ar.3r with an age of 12.75 ± 0.25 Ma [4].

6.2. Vallesian (MN9 and MN10)

The lower Vallesian boundary was defined by Crusafont [18] as the first appearance datum (FAD) of the equid *Hipparion* in western Europe. This FAD of *Hipparion* (or the '*Hipparion* datum') was originally assumed to be a synchronous event [32,33]. This assumption was questioned by Sen [34], who stated that ecological and paleogeographical factors had not been taken into account and suggested the *Hipparion* datum to be a diachronous event. So far, however, neither synchrony or diachrony of the *Hipparion* datum has been proven because of the lack of reliable chronological data and limits of biostratigraphic resolution of large mammal faunas.

The main arguments for the assumed diachrony of the *Hipparion* event were related to radiometric dating from sites in Germany (Höwenegg) and Algeria (Bou Hanifia). The Höwenegg locality yielded two radiometric dates; 12.4 ± 1 Ma on hornblende [35] and 10.8 ± 0.4 Ma on whole rock analysis [36]. It has already been stated by Sen [34] that the radiometric dating of the hornblende is rather questionable and the age of 10.8 ± 0.4 Ma is preferred. At Bou Hanifia, biotite-rich ash layers were dated to 12.18 ± 1.03 Ma [37] and later redated at 12.03 ± 0.25 Ma, but they only indicate a maximum age for the Bou Hanifia Formation. An extrapolation to the *Hipparion*-bearing horizon is impossible because of a large stratigraphic gap of approximately 100 m between the ash layer and the fossil locality. The radiometric datings at Bou Hanifia cannot, therefore, be used in discussing the age of the Aragonian/Vallesian boundary.

In the Vallès–Penedès Basin, the association of *Hipparion* with *Megacricetodon ibericus* in localities CCN-20, CCN-22 and RK11 (Montagut section) indicates a lowermost Vallesian age. There, the earliest occurrence of *Hipparion*, marking the lower MN9 boundary, occurs in chron C5r.1n, at 11.1 Ma [5,6]. In Torremormojón, the first record of *Hipparion* occurs in association with *Cricetulodon* in chron C5n.2n at an age of 10.3 Ma (TM 4). The appearance of a typically Vallesian rodent fauna is, however, recorded in the same section somewhat earlier (TM 5). In Torremormojón, the MN7–8/MN9 boundary is located between fossil localities TM6a and TM5, indicating an age of 10.9 ± 0.3 Ma. The age determinations for the MN7–8/MN9 boundary in both basins are in good agreement and give a best age estimate in chron C5r.1n at 11.1 Ma.

The MN9/MN10 (lower/upper Vallesian) boundary is associated with the entry of *Progonomys hispanicus* [38,16]. The so-called Vallesian event corresponds to a major biotic crisis with numerous extinctions and radiations which affected diverse orders of mammals in different ways [39]. This abrupt faunal change is most evident for the rodents. The Vallesian event profoundly affected three families of middle Miocene rodents (cricetids, glirids and eomyids), and a number of eastern, Asian, macromammal elements appear in western Europe at the same time. The MN9/MN10 boundary is well recorded in the Les Fonts and Montagut sections (Vallès–Penedès Basin) in chron C4Ar.3r, at 9.7 Ma [5,6]. The results again agree with the one obtained from Torremormojón, where the MN9/MN10 boundary is recognised between localities TM 2 and TM 1, giving an age of 9.7 ± 0.1 Ma.

6.3. Turolian (MN11–MN13)

The base of the Turolian coincides with the base of MN11. In the La Gloria section, MN10 and MN11 associations allowed the determination of the MN10/MN11 (Vallesian/ Turolian) boundary at an age of 8.7 ± 0.1 Ma. The results from the El Bunker section show that MN11 extends at least to the lower part of chron C4n.2n. So far, this is the only age determination for the V/T boundary and it is in agreement with previous dating of lowermost MN11 faunas. The Kayadibi locality (lowermost MN11) in Turkey is estimated between two radiometrically (K–Ar) dated ignimbrites of 9.4 ± 0.2 Ma and 7.95 ± 0.25 Ma [40]. Quarry X from Samos (lower Turolian; Greece) has a radiometric age near 8.5 Ma [41]. Turolian faunas are not dated in Vallès–Penedès, but uppermost MN10 faunas with *Hipparion* cf. *mediterraneum* are correlated to the lower part of chron C4An, at about 9.0 Ma. This age closely fits with that of the base of the Turolian as determined in the Teruel Basin.

The MN11/MN12 (middle Turolian) boundary is correlated to magnetostratigraphy in the Cabriel Valley section [2] and recalibration to CK95 gives an age of 7.5 ± 0.1 Ma.

7. Conclusions

The good magnetostratigraphic results from ten sections in Spain show that an almost complete stratigraphic record is present from approximately 18 to 6 Myr (Fig. 8). The biostratigraphic record in this succession is extremely rich and dense, which facilitates the construction of a detailed biozonation and the study of paleoclimatological and paleoenvironmental changes during the middle to late Miocene. Correlation of the magnetic polarity patterns of our sections to the GPTS of CK95 is generally straightforward, except for the top of the El Bunker section where major hiatuses or significant changes in sedimentation rate must have taken place.

For the first time, we have established a detailed chronology for the middle to late Miocene continental record in Spain. Seven successive MN zone boundaries are determined and dated in sections which contain faunas of two or more successive zones in superpositon (Table 1, Fig. 8). The previous magnetostratigraphic dating of the onset of a global mid-Miocene 14.1 Ma cooling event [4] is confirmed, although this event is now placed in the upper part of zone MN5, following its new definition. The major biotic crisis, marked by the paleofaunal changes, on which the distinction between MN9 and MN10 is based (intra-Vallesian crisis [39]) and which includes the entry of *Progonomys* into Europe, is well dated in chron C4Ar.3r at 9.7 Ma [5,6].

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