



A review of the European Neogene Mammal zones from integration of litho-, bio- and magnetostratigraphy in the Teruel Basin

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ABSTRACT

The northern sector of the Teruel Basin (Spain) houses a dense and continuous record of late Neogene mammal fossil sites, as well as numerous biostratigraphic and magnetostratigraphic information making it a reference basin to define and refine the European mammal biostratigraphy from the Vallesian to the Villafranchian. The Neogene mammal chronology is in ongoing revision, and distinct correlations between basins and Europe provinces have been proposed based on their relative ages. New calibration methods based on numerical modelling have allowed the absolute ages of the paleontological sites to be refined. Nevertheless, some discrepancies arise, evidencing that anchoring between absolute ages and mammal fossil record would benefit from a stronger stratigraphical framework. This work provides such a robust 3D stratigraphic framework of the whole basin that, together with magnetostratigraphy, allows establishing an accurate chronostratigraphic model and hence a precise chronology of sedimentary units and mammal sites. The absolute age of MN zones, or mammal stages, in the Teruel Basin has been revised on the basis of a detailed and confident stratigraphic correlation, and updated to the most recent Geomagnetic Polarity Time Scale. In particular, new accurate ages have been proposed for the boundaries MN 9/10 to MN 16/17 from data exclusively located in the Teruel Basin, with a precision generally of 0.1–0.2 Ma.

1. Introduction

The definition of stratigraphic units in continental basins as a reference for dividing the sedimentary record upon chronological (relative or absolute) bases, as well as the correlation between different geological provinces, continue to be a matter of special interest for geologists. The first and most widespread method used to date terrestrial deposits in Cenozoic basins is based on mammal fossil remains. In this way, the northern Teruel Basin has been a key area for the proposal and improvement of the Mammal Neogene zones (MN zones; Mein, 1975), the European Mammal units (MN units; Bruijn et al., 1992), as well as the European Land Mammal Ages scale (ELMA; Sen, 1997) or the European Land Mammal Mega-Zones (ELMMZ, Steininger, 1999). The correlation of local magnetostratigraphy with the Geomagnetic Polarity Time Scale (GPTS) is partially based on the age provided by the paleontological sites, so the reliability and precision of the former will be conditioned by the reliability provided by the latter. However, this

methodology entails several difficulties; among others, the lack of vertical continuity of the faunal assemblages in stratigraphic successions, demonstrated superposition between paleontological sites, sedimentary hiatuses, and fauna migration and extinction events (e.g. Lindsay, 2003; Dam, 2003).

During the last decades absolute dating methods as magnetostratigraphic, radiometric or astrochronological ones, have contributed enormously to unraveling some of these topics, such as the age calibration of mammal zones. However, new questions have arisen mainly related to the degree of isochrony of the mammal-based boundaries (e.g. Fahlbusch, 1991; Agustí et al., 2001; Abdul Aziz et al., 2003; Koufos, 2013). This has led to the proposal of several nomenclatures and conceptual approaches depending on whether the mammal-based units are considered as biochronological, biostratigraphic, chronostratigraphic or geochronological units, in some cases used as synonyms (e.g. Lindsay et al., 1990; Lindsay, 2003; Dam, 2003; Lourens et al., 2004; Hilgen et al., 2012). The multivariate analysis of information included in fauna

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catalogs, through the application of the appearance event ordination (AEO) method of [Alroy \(1994\)](#), or the maximum likelihood appearance event ordination (ML AEO; [Alroy, 2000](#)), is becoming increasingly generalized. Accurate source data are highly desirable to apply such procedure and assign absolute ages to uncalibrated mammal units.

Significant contributions to solve these issues must necessarily arise from in-depth investigation of basins with a great mammal localities wealth. The continental Teruel Basin has been proved to be an exceptional area for Neogene vertebrate studies, both on micro- and macro-mammal faunas. This basin has been a reference for international paleontologists since 1950 due to the huge number of paleontological sites, the variety of Neogene fauna assemblages and the excellent fossil conservation. For these reasons, the record of mammal fossils in the northern sector of the basin has contributed substantially to studies focused on the evolution of the European vertebrates. Despite the large number of fossiliferous sites, as well as the existence of several magnetostratigraphic sections, the chronostratigraphic framework of the northern part of the Neogene Teruel Basin is not yet well known because an accurate stratigraphic framework was still lacking. Although approximately 40 local stratigraphic profiles have been studied in the area (e.g. [Weerd, 1976](#); [Godoy et al., 1983a, 1983b](#); [van Dam, 1997](#); [Alonso-Zarza et al., 2000, 2002](#)), and the main stratigraphic and sedimentological characteristics have been established, little or nothing had been done to ascertain their correlation and the overall stratigraphic architecture of the basin. Some correlation proposals were fundamentally based on lithological criteria, forgetting the frequent and rapid lateral facies changes, which are typical in small terrestrial basins as the Neogene Teruel Basin. This situation has led to some paradoxical situations such as the proposal of the Turolian stratotype section in Los Mansuetos area ([Crusafont, 1965](#); [Calvo et al., 1999](#)), whose high geological complexity has not had a satisfactory stratigraphic and structural interpretation ([Calvo et al., 1999](#); [Lafuente, 2011](#); [Gutiérrez et al., 2012](#)) until the PhD Thesis of [Ezquerro \(2017\)](#). It is therefore not surprising that other proposals for the definition of stratotypes, such as the Alfambrian ([Moissenet et al., 1990](#)), have not been consolidated. In short, the proliferation of paleontological works in this basin during the last five decades is not in agreement with the absence of a precise stratigraphic framework.

This work proposes a robust stratigraphic framework based on an intensive study that includes logging and correlation of new stratigraphic sections and integration of all the available paleontological and magnetostratigraphical data. It has allowed the chronological bracketing of the northern Teruel Basin Neogene infill to be reviewed. The establishment of a integrated bio- and chronostratigraphic model, mainly based on stratigraphic relationships between lithological units, fossil sites and magnetostratigraphic profiles, has strengthened the absolute age calibration of mammal sites. The age of boundaries between MN zones 9 to 17 is reviewed and discussed. Our results will help to refine the European mammal chronology and to clarify future correlations between different Iberian basins or paleontological provinces.

2. Geological setting

2.1. The Neogene Teruel Basin

The Neogene Teruel Basin is an elongated, NNE-SSW trending intra-mountain graben situated in the central-eastern Iberian Chain, eastern Spain ([Fig. 1a](#)). Breaking the NW-SE trending contractive structure of the chain ([Fig. 1b](#)), this and other extensional basins (Maestrat grabens or the Jiloca Graben) were developed associated to the rifting of the Valencia Trough (Mediterranean Sea) that has been affecting the central-eastern part of Iberia since the Early-Middle Miocene ([Álvaro et al., 1979](#); [Capote et al., 2002](#)). The southern sector of the Teruel Basin (Teruel-Mira) is an asymmetric graben that, through a transition zone (nearby Teruel city), passes to a half-graben in the northern sector (Teruel-Perales de Alfambra, [Fig. 1b](#)). The transition zone is structurally

complex due to the connection with the Jiloca Basin and the existence of an ensemble of diversely oriented faults: Concud, Tortajada, Teruel, Los Mansuetos and Valdecebro faults. In the northern sector, the basin structure is controlled by faults and fault zones in its eastern margin ([Moissenet, 1983](#); [Simón et al., 2012](#); [Ezquerro, 2017](#); [Ezquerro et al., 2019, 2020](#); [Liesa et al., 2019](#)), with N-S (El Pobo Fault Zone and Cabigordo fault) and NE-SW (Perales and Tortajada faults) directions. In the hanging-wall block, Neogene rocks are tilted towards the eastern, active margin, forming a gentle but widely recognizable rollover monocline.

The sedimentary fill of the Teruel Basin, up to 500 m in thickness, is made of Neogene terrigenous, carbonate and gypsum rocks. These represent alluvial and lacustrine sedimentation in alluvial fans sourced in the margins that passed towards the central basin areas to palustrine-lacustrine environments ([Weerd, 1976](#); [Moissenet, 1980](#); [Godoy et al., 1983a, 1983b](#); [Alonso-Zarza et al., 2000](#); [Ezquerro et al., 2014, 2019](#); [Ezquerro, 2017](#)). In the northern Teruel Basin, the syn-rift infill spans from the earliest Vallesian (Late Miocene, ca. 11.2 Ma) to the latest Villafranchian (Late Pliocene-Early Pleistocene, ~1.8 Ma) ([Ezquerro, 2017](#); [Ezquerro et al., 2022](#)). Several stratigraphical divisions have been proposed, in which, although different criteria were used for defining the units, the large lithologic assemblages and their ages are generally similar to each other ([Fig. 2](#)).

[Weerd \(1976\)](#) proposed four formations: *Peral Fm* (alluvial terrigenous facies), *Alfambra Fm* (lacustrine carbonates), *Tortajada Fm* (lacustrine evaporites) and *Escorihuela Fm* (alluvial, palustrine and aeolian deposits). For mapping purposes, [Godoy et al. \(1983a, 1983b\)](#) used eight lithological informal units, alternating terrigenous (*Unidad Detrítica Inferior*, *Rojo 1*, *Rojo 2* and *Rojo 3*) and carbonate units (*Calizas Inferiores*, *Páramo 1* and *Páramo 2*), and culminated by the alluvial *Villafranchian Glacis*. These units, based on lithology, subdivided the formal ones by [Weerd \(1976\)](#) and have been widely used for lithostratigraphic description. Later on, [Alonso-Zarza et al. \(2000\)](#), considering vertical evolution of sedimentary environments, established five genetic units (*I*, *II*, *III*, *IV* and *V*), whose age were later revised ([Alcalá et al., 2000](#); [Sancho et al., 2000](#); [Anadón et al., 2004](#); [Alonso-Zarza et al., 2012](#)). While those of previous authors were proposed for the entire basin, these genetic units were defined in two separated areas: Tortajada and Villalba Alta, respectively ([Fig. 1b](#)). Several problems arise in their correlation, both between those areas and with respect to units defined by other authors; e.g. the unit *IV* is correlated with the *Escorihuela Fm*, but neither their age nor their stratigraphic position match exactly. Recently, based on a throughout stratigraphical, sedimentological, and structural study of the northern Teruel Basin, [Ezquerro et al. \(2014\)](#) and [Ezquerro \(2017\)](#) proposed ten vertically-stacked megasequences (M1 to M10), which correspond to six genetic units (TN1 to TN6) in the sense of [Pardo et al. \(1989\)](#).

2.2. Paleontological studies

The paleontological record in the Teruel Basin is exceptionally long, quite continuous and dense. Early paleontological studies date from the early 18th century, when fossils north of the Concud village (nowadays the Barranco de las Calaveras mammal site) were described ([Feijoo, 1736](#)). Since 1800, with the birth of Paleontology as a geological discipline, the first systematic analysis considered such remains as belonging to non-human mammals ([Ezquerro Bayo, 1845](#); [Maestre, 1845](#)). The discovery of new mammal sites (e.g., Orrios and Los Mansuetos sites) drove the first biostratigraphic studies, which led to the proposal of a Miocene age for both fauna and sediments (e.g. [Ezquerro Bayo, 1850](#); [Gervais, 1852](#); [Vilanova and Piera, 1863](#); [Cortázar, 1885](#)). With the turn to the 20th century, continuous work in the Teruel Basin (Cerro de la Garita and Los Aljezares mammal sites) revealed the presence of *Hipparion*, *Gazella*, *Hyaena*, *Capreolus*, etc. among the most important large mammal taxa ([Hernández-Pacheco, 1914, 1916, 1921, 1924, 1930](#)), and small mammals ([Navás, 1922](#); [Margalef, 1947](#)).

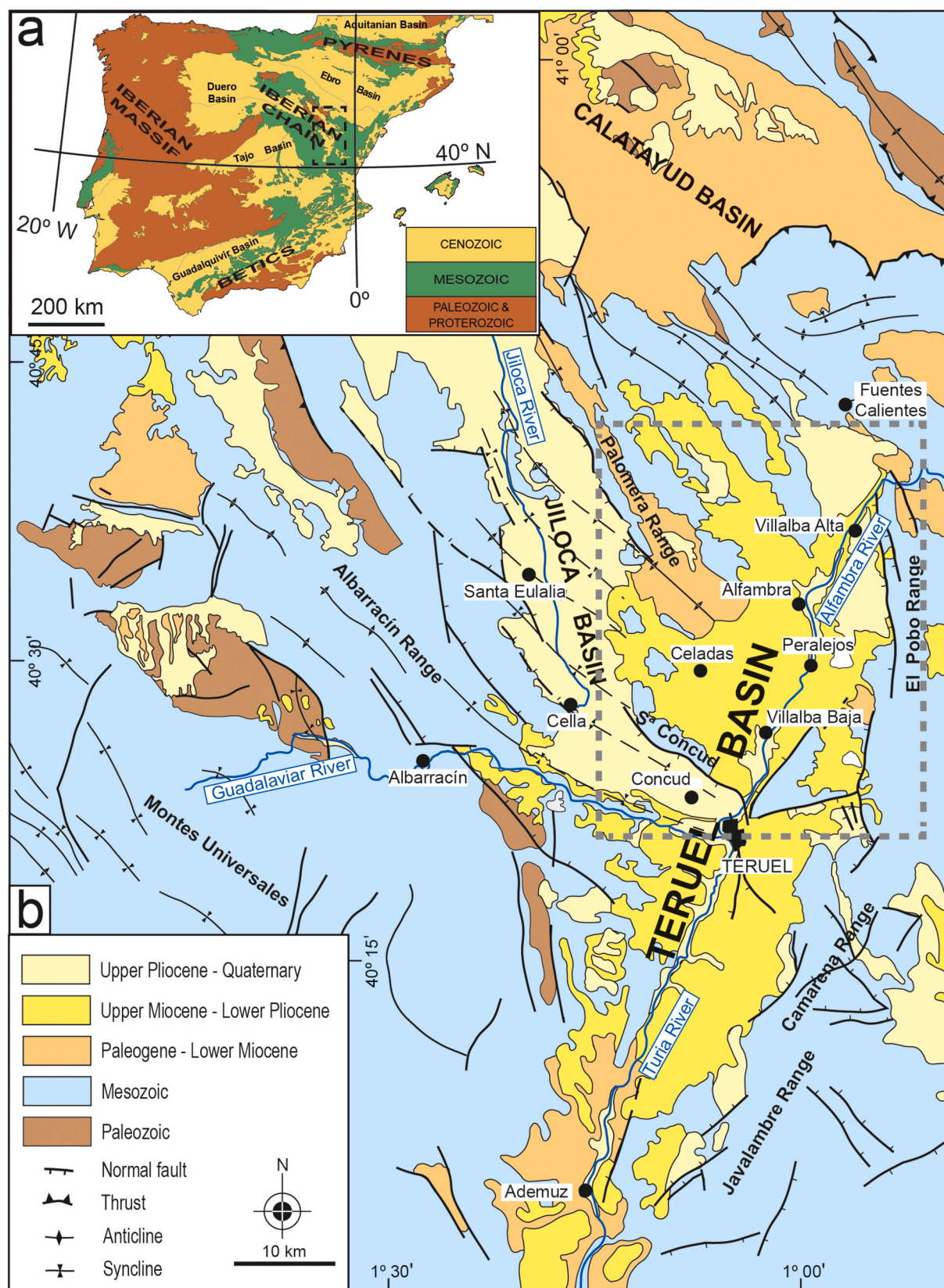


Fig. 1. (a) Location of the Teruel Basin in the eastern Iberian Peninsula. (b) Geological map of the northern sector of the Teruel Basin.

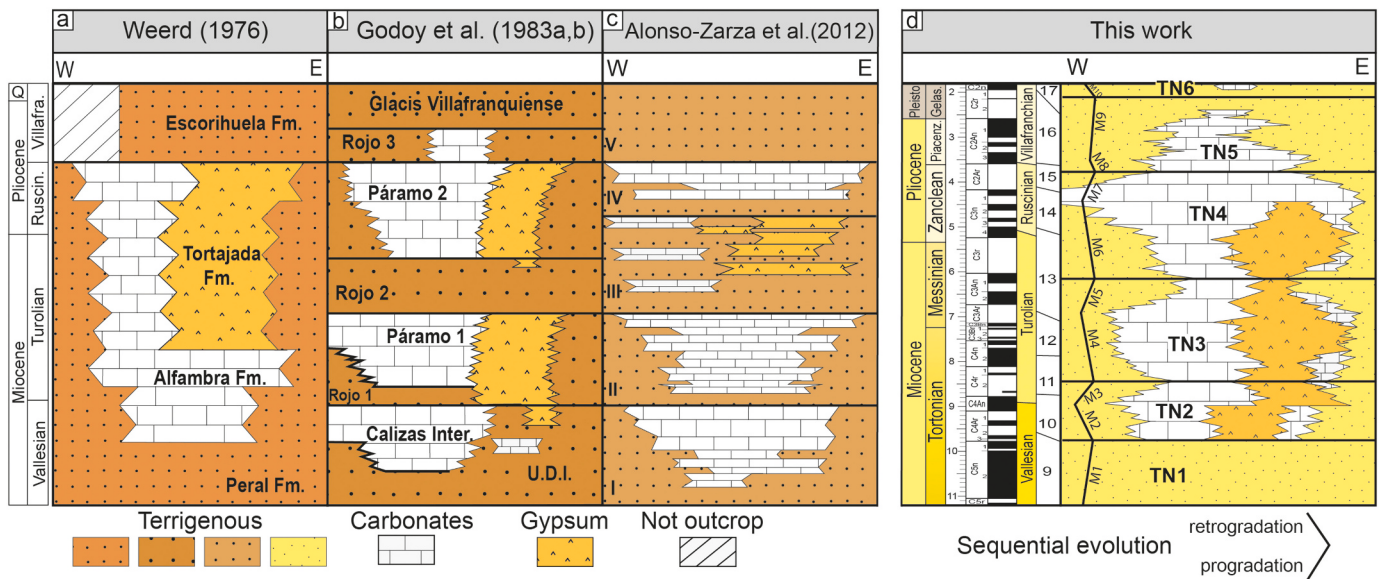


Fig. 2. Main stratigraphic divisions proposed for the Neogene-Quaternary filling of the northern sector of the Teruel Basin. The diagrams show a correlation of units according to an approximate orientation W-E. (a) Formations by Weerd (1976). (b) Simplified scheme of informal lithostratigraphic units by Godoy et al. (1983a, 1983b). (c) Stratigraphic division by Alonso-Zarza et al. (2012), which completes those by Alcalá et al. (2000), Alonso-Zarza and Calvo (2000) and Alonso-Zarza et al. (2002). (d) Genetic units and megasequences after Ezquerro (2017). Carbonate and saline facies can show different arrangements towards the margins, especially in TN5 and TN6 units (see Fig. 8 and Supplementary Figures).

Since 1950, the increasing interest in mammal paleontology has turned the Teruel Basin into a focus of interest (Truyols, 1961; Crusafont, 1962; Crusafont et al., 1963; Crusafont and Truyols, 1964; Adrover, 1964) that culminated with the definition of the Turolian stratotype (Crusafont, 1965), a new Upper Miocene continental stage. Its definition was based on the high diversity of fauna, especially *Hipparion* and *Mastodon*, although *Gazella* and *Bovidae* were also important. The type section was approved by many researchers (Marks, 1971; Alberdi, 1974; Adrover and Esteras, 1974; Adrover, 1962, 1963, 1975; Robles, 1975; Aguirre et al., 1975; Alcalá et al., 1994). The first regional paleontological and stratigraphical study of the northern Teruel Basin was performed by Weerd (1976) with a clear biostratigraphic purpose. Numerous rodent species were defined and multiple new mammal sites were located.

In 1975, the proposition of the European Mammal Neogene (MN) zones by Pierre Mein supposed a challenge in paleontological studies, in which the Teruel Basin was a strategic area. The amount of taxonomic, stratigraphic and chronological information, here and in the whole Europe, increased greatly. Research on small mammals in the Teruel Basin (from the Miocene to the Pleistocene) has been very prolific, in both new fossil sites and species (Adrover, 1962, 1975; Adrover and Mein, 1996; Adrover et al., 1976, 1978, 1982a–c, 1984, 1986, 1988, 1993a,b; Brujin, 1966; Brujin and van Meurs, 1967; Brujin and van Meurs, 1967; Freudenthal, 1966, 1967; Brujin and Mein, 1968; Michaux, 1971; Alberdi, 1974; Alcalá, 1986, 1994; Alcalá et al., 1991; Alcalá and Montoya, 1998a, 1998b; Daams et al., 1998; Montoya et al., 2001a, 2001b; Salesa et al., 2003, 2010; Hordijk et al., 2015). Several syntheses on the paleontological knowledge of the basin stand out, and represent key contributions to the biostratigraphic scale (Adrover, 1975, 1981, 1986; Besems and Weerd, 1983; Mein et al., 1983, 1990; Brujin et al., 1992). More recently, a useful synthesis of small mammal sites was firstly used to propose local zoning (van Dam, 1997; van Dam et al., 2001), and then to interpret palaeoclimate conditions (van Dam and Weltje, 1999; van Dam, 2006; van Dam et al., 2006; van Dam and Reichart, 2009).

Studies on large mammals have shown a parallel trend, with numerous works dealing with a huge variety of genera: *Canis* (Pons Moyà and Crusafont Pairó, 1978; Alcalá, 1992, 1994), *Eucyon* (Rook,

2009), *Bovidae* (Alcalá et al., 1991; Alcalá, 1992, 1994; Alcalá et al., 2005; Alcalá and Morales, 2006), *Giraffidae* (Alcalá, 1992, 1994; Alcalá and Montoya, 1994), *Cervidae* (Alcalá, 1992, 1994; Azanza and Montoya, 1995; Azanza et al., 2000), *Caprine* (Alcalá and Morales, 1997), *Rhinocerotidae* (Cerdeño and Alcalá, 1989; Alcalá, 1992, 1994), *Hippopotamidae* (Alcalá and Montoya, 1998a; Martino et al., 2021), *Ursidae* (Montoya et al., 2001b), *Paramachairodus* (Salesa et al., 2003, 2010), *Hyaena* (Pesquero et al., 2010), and perhaps the most studied, *Hipparion* (Sondaar, 1961; Alberdi, 1974, 1986; Alberdi and Alcalá, 1978, 1990; Isidro et al., 2001; Pesquero, 2003; Pesquero et al., 2006, 2011).

Paleontological studies have also dealt with paleoecological (Fernández-Marrón, 1972; Albasa et al., 1997), paleobotanic (Gregor and Günther, 1985), and taphonomic issues (Pesquero and Alcalá, 2008; Pesquero et al., 2010, 2012, 2013), including, e.g., fracture of *Hipparion* metapodes (Alcalá and Escorza, 1988) or long bone orientation in the Conclud locality (Alcalá et al., 1999). Studies on the plenty of continental mollusks (Albasa and Robles, 2006), bioclimatology (Azanza et al., 2000; Renaud and van Dam, 2002; Hernández Fernández et al., 2007), or the isotopic signature of *Hipparion* teeth related to paleoclimatology (Domingo et al., 2007, 2009, 2013; van Dam et al., 2020) also stand out.

2.3. Magnetostratigraphical studies

Magnetostratigraphic studies in the Teruel Basin have not been as profuse as paleontological ones, but they are essential for providing a time frame to both, the mammal sites and the Neogene sedimentary fill. Most of them were focused on calibrating the absolute age of both the most significant paleontological sites and the boundaries of the MN zones. As far as we know, ten magnetostratigraphic sections (La Roma, Masada Ruea, Masada del Valle, La Gloria, El Bunker, Orrios, Villalba Alta Río, Villalba Alta, Escorihuela, and Conclud) had been carried out in the northern Teruel Basin (Krijgsman, 1996; Krijgsman et al., 1996; Opdyke et al., 1997; Garcés et al., 1999; Kraviev et al., 2003). Recently, our research group carried out a new magnetostratigraphic section (Masada Cociero) located north close to the city of Teruel, which has allowed to establish the chronological age of the most recent paleontological site of the basin (RTC, Ezquerro et al., 2016).

As a result, the northern sector of this basin has one of the most

complete magnetostratigraphic records for continental deposits worldwide. It extends from the Vallesian (Tortonian) to the Villafranchian (Gelasian), making the basin a reference for the European Neogene Mammal scale (e.g. Agustí et al., 2001; Vangengeim et al., 2005; Hilgen et al., 2012). The magnetostratigraphic sections are distributed throughout the basin from the vicinity of Teruel city (to the south) to Villalba Alta village (to the north) and cover practically the entire time lapse represented by the outcropping sedimentary infill. Half of them are located in the southern part of the study area (profiles of La Roma, Masada Ruea, Masada del Valle, La Gloria and El Bunker), covering the lower part of the stratigraphic record (Vallesian to Turolian, zones MN10 to MN13). The rest (Orrios, Villalba Alta Rio, Villalba Alta, Escorihuela, Concud and Masada Cociero) are located, except the last two, in the northern part of the study area and cover the middle-upper part of the stratigraphic record (Ruscinian to Villafranchian, zones MN14 to MN17).

3. Methodology

To achieve our main objective, the methodological procedure has involved integration of valuable information on stratigraphy, sedimentology, paleontology and magnetostratigraphy of the Teruel Basin.

Stratigraphical works consisted of detailed logging, study and correlation of 72 profiles located along the northern sector of the Teruel Basin that represent ~5000 m of sedimentary thickness. The profiles were selected along nine transverse sections (transects), trending approximately W-E or NW-SE, with an average spacing of 4 km between each other (Fig. 3). They were named, from south to north, Teruel (Te), San Blas (SB), Tortajada (To), Celadas (Ce), Peralejos (Pe), Alfambra (Al), Orrios (Or), Villalba Alta (Vi), and Los Alcamines (LA). Each transect includes 6 to 13 stratigraphic profiles that can be easily identified by the abbreviation of the transect name and the profile number in the transect, in ascending order from west to east. The study also involved sedimentological analysis (Ezquerro, 2017), including identification and interpretation of lithofacies according to classical criteria (lithology, texture, geometry of sedimentary bodies, sedimentary structures, fossil content...), establishment of mappable lithofacies associations, and analysis of their vertical evolution by defining megasequences and genetic units following the methodological approach of Pardo et al. (1989). The megasequences are based on changes of grain-size and facies associations at basin scale, where the boundaries between megasequences correspond to changes from coarsening- to fining-upwards trend or *viceversa*. The maximum in grain size or progradation are considered boundary of the genetic unit (Pardo et al., 1989).

The 3D model was based on the recognition and correlation of numerous key stratigraphic levels (20 guide levels) that, due to their morphological expression, lithological or structural features and faunal content, were easy to recognize and follow physically between different outcrops (either in place or by means of aerial photography). Thus, a robust correlation of the stratigraphic profiles in each transect and between adjacent transects was accomplished. The guide levels were mapped at basin scale through a photogeological study using stereoscopic pairs of aerial photographs (scale 1:33000 and 1:18000) and high-resolution digital satellite images (50 cm/pixel). The stratigraphic correlation allowed the guide levels to be chronologically ordered; thereafter, they were numbered correlatively, from oldest to youngest. In some cases, several levels from different profiles are stratigraphically located very close to each other (<3 m) and was not possible to establish their relative position with accuracy. These levels were gathered in a cluster and labeled with the same number. The correlation between the guide levels and the magnetostratigraphic sections allowed their absolute dating.

The bio-chronostratigraphic model of the basin has been achieved from an exhaustive bibliographic review of the location of mammal sites with biostratigraphic meaning (relative dating) and

magnetostratigraphic profiles (numerical dating), which could therefore be linked to the 3D stratigraphic-sedimentological model. Paleontological sites were classified according to the confidence in their stratigraphic position within our 3D model, based on their proximity to the stratigraphic profiles and magnetostratigraphic sections. Three categories were distinguished: 1 (accurate), 2 (fairly certain), and 3 (estimated). Category 1 corresponds to mammal sites located in a magnetostratigraphic section (or a few meters from them), making possible an accurate correlation with our stratigraphic profile. Category 2 corresponds to sites located in our stratigraphic profiles, but not associated with magnetostratigraphy, so that only their relative position with respect to some correlation level is available. Category 3 corresponds to sites not directly related with stratigraphic or magnetostratigraphic sections, their chronostratigraphic position being bracketed between those of two consecutive guide levels. Based on the foregoing criteria, the bio-chronostratigraphic model of the northern Teruel Basin has been framed within the continental biostratigraphic scale represented by Mammal Neogene zones (MN zones; Mein, 1975), the European Land Mammal Ages scale (ELMA), and the global magnetostratigraphic scale (GPTS) of Gradstein et al. (2020).

4. The 3D stratigraphic model of the northern Teruel Basin

The sedimentary fill almost hold the geometry and structure of the basin, hampering the entire definition of the stratigraphic architecture of the northern sector of the Teruel Basin by several factors: i) the halfgraben synclinal geometry of the basin (Liesa et al., 2019; Ezquerro et al., 2020), which determines that the sedimentary succession was mainly exposed in the central areas but only partially at the basin margins (remaining the oldest materials in subsurface positions); ii) the weak Quaternary incision of the Alfambra River, running longitudinally through the basin, and of the small ravines sourced from the basin boundaries (Sánchez-Fabre, 1989), which prevents the lower succession to crop out in the central parts of the basin; iii) the very scarce subsurface information, limited to a few shallow wells made for hydrogeological purposes. Seismic profiles are not available, and a complete characterization of the geometric arrangement and stratigraphic architecture of the *syn-rift* sedimentary sequence is not possible.

As a result, as explained before, the guide levels (Fig. 3) enabled correlation within each transect but also between adjacent transects (Fig. 4). Supplementary note 1 includes a brief description of the levels and groups used for correlation, the stratigraphic profiles and transects in which they have been recognized, as well as additional information on the stratigraphic correlation procedure in each case. Supplementary figs. 1 to 9 show nine 2D stratigraphic panels (or transects) traverse to the basin axis with correlated stratigraphic profiles, megasequences and genetic units; they also include the stratigraphic position of the mammal sites with biostratigraphic significance and the magnetostratigraphic sections on which the chronostratigraphic model is based.

The levels with higher lateral continuity (levels 6, 7 and 9) can be followed from Teruel to Alfambra transects. Level 9, due to its higher continuity and significance in relation to previous stratigraphic divisions, was chosen as main datum for the 3D stratigraphic model. In addition, levels 10, 11, 12, 14, 15, 18 and 19, although much less extensive, have been key for correlation in the northernmost area, between Orrios and Los Alcamines transects (Fig. 4). Due to their lateral extension and vertical distribution, levels 1 to 9 enable a good litho- and chronostratigraphic division of the lower part of the Neogene succession in the central and southern sectors of the basin (between Alfambra-Teruel). Levels 10 to 14 allow the middle-upper of the infill to be subdivided in the northernmost sector (Orrios-Villalba Alta). Levels 15 to 20, only recognized in Orrios-Villalba Alta and San Blas (south-western area) transects, allow the characterization and analysis of the uppermost part of the sedimentary fill.

The analysis of the lateral and vertical relations between the correlation levels (Fig. 3 and Supplementary Figs. 1 to 9), as well as the 3D

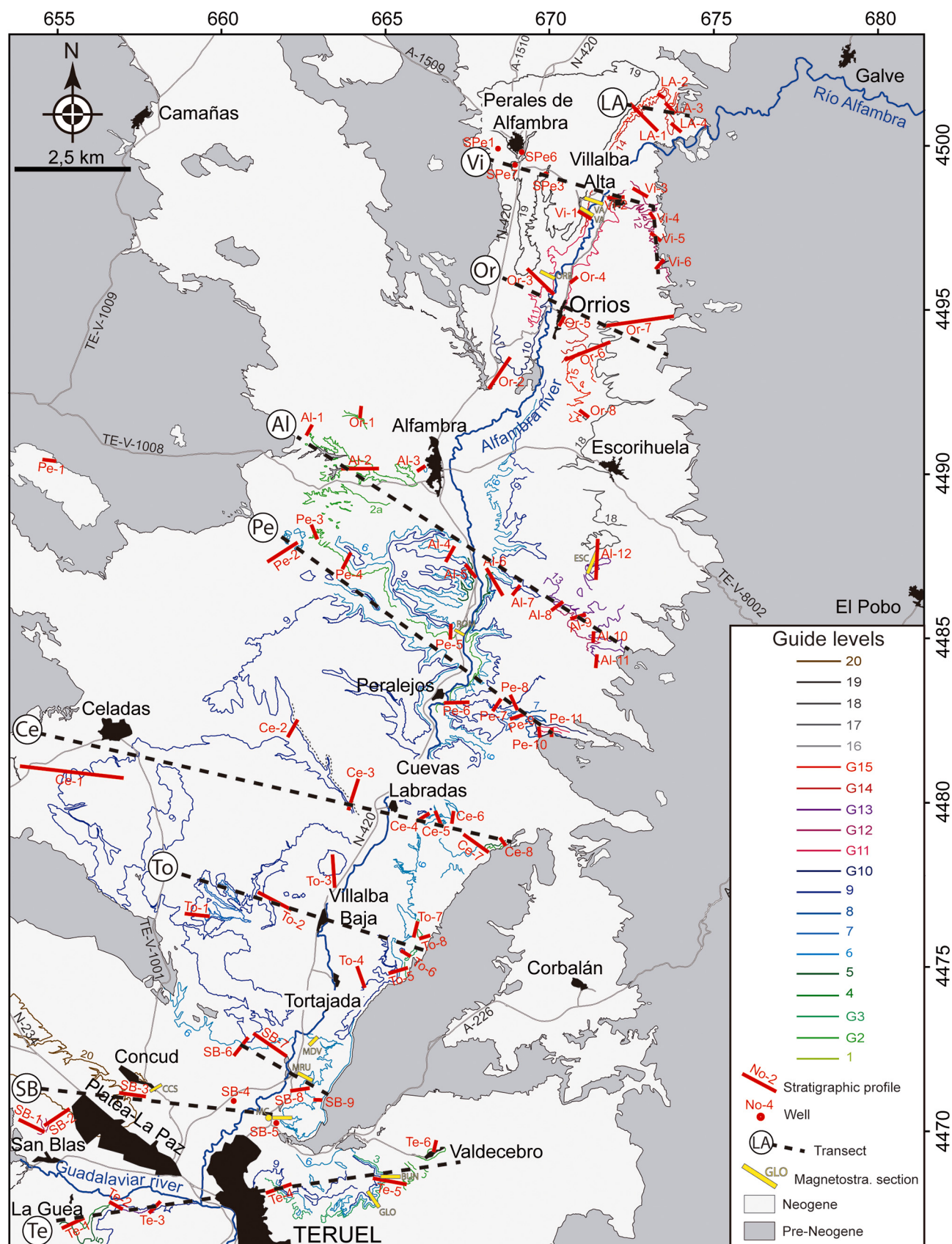


Fig. 3. Location of stratigraphic profiles, magnetostratigraphic sections and boreholes on which the 3D stratigraphic model of the northern sector of the Teruel Basin is based (see explanation in the text). Guide levels are mapped. For correlation, the information has been grouped into transects: Teruel (Te), San Blas (SB), Tortajada (To), Celadas (Ce), Peralejos (Pe), Alfambra (Al), Orrios (Or), Villalba Alta (Vi) and Los Alcamines (LA).

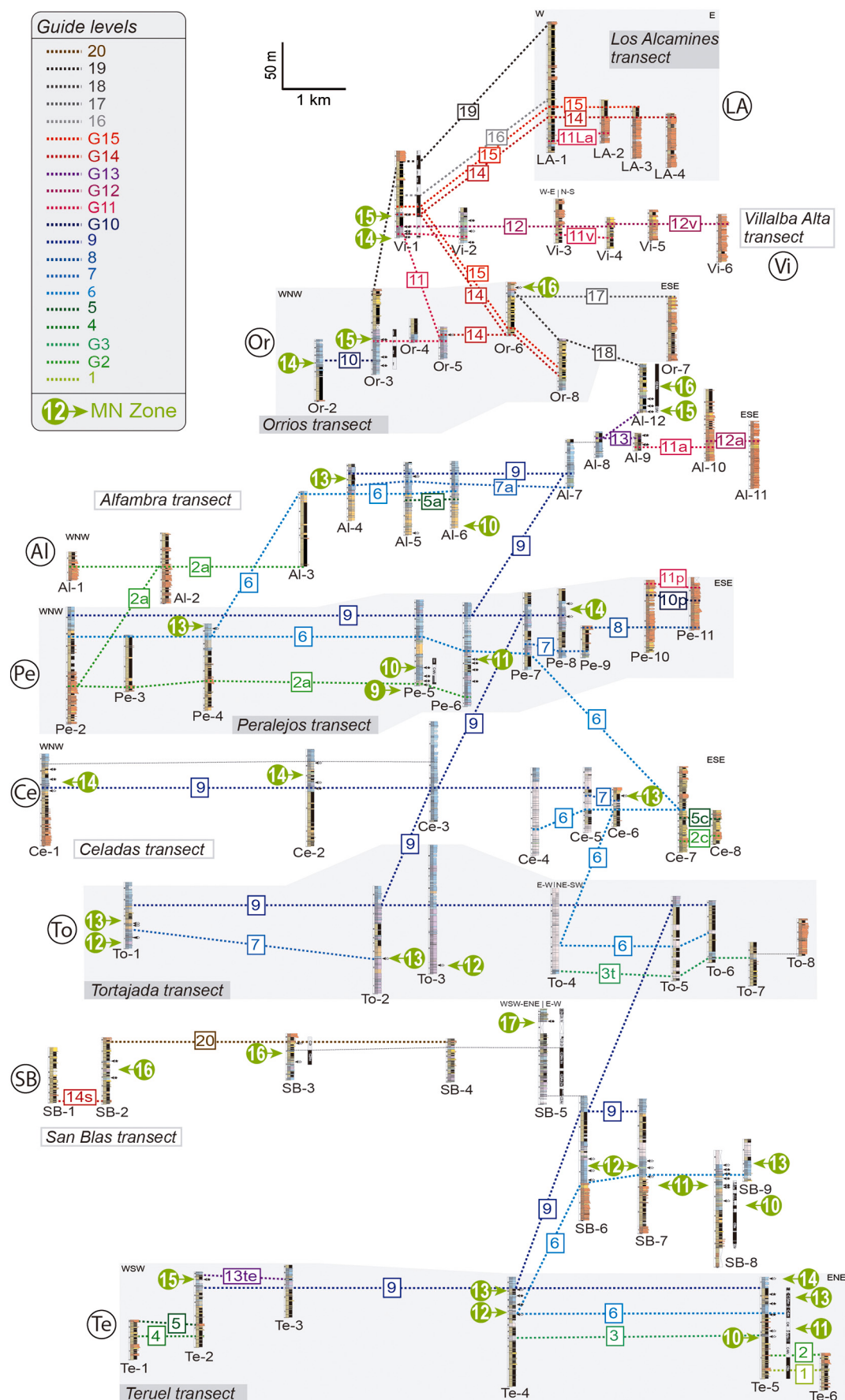


Fig. 4. 3D stratigraphic panel in the northern Teruel Basin mostly based on physical correlation of guide levels (see Supplementary notes 1 and 2).

model, allow to define an accurate stratigraphic division for the whole basin. The Neogene sedimentary fill can be divided into six genetic units (TN1 to TN6) that comprise 10 megasequences (M1 to M10). The odd-numbered, coarsening-upwards sequences correspond to alluvial progradations, and the even-numbered, fining-upwards ones to retrogradations (Ezquerro, 2017; Ezquerro et al., 2020). Boundaries between these megasequences correspond to stratigraphical trend variations, based on grain-size and facies association changes, from alluvial retrogradation to progradation and *vice versa*, and related lacustrine expansions and retractions. Five major progradations have been recognized at basin scale, whose maxima have been proved to be isochronous and correspond to the boundaries (B1 to B5) between the genetic units (Fig. 2). The deformation structures (unconformities, growth strata, etc.) related to these boundaries reflect that alluvial progradations were related to tectonically active periods. Throughout the basin, TN1 to TN4 units crop out in almost continuity, from Teruel to Alfambra localities, while TN5 and TN6 are limited to the northern and southern areas.

5. Biostratigraphical constraints: stratigraphical position and ascription to MN zones of the Neogene mammal sites

As explained in section 2.2, numerous works have been focused on the paleontological record (mainly small and large mammals) of the northern Teruel Basin. In most cases, fossiliferous sites are situated in marl, marly limestone or dark mudstone levels, all of them deposited in lacustrine-palustrine environments, but some localities are associated with reddish mudstone from distal alluvial zones (van Dam et al., 2001; Ezquerro, 2017). Some of the works include valuable notes on the discovery of the paleontological sites, their name, synonyms, ascription to the MN zone, and publications of reference (Adrover, 1986; Mein et al., 1983, 1990; Alcalá, 1994; van Dam, 1997; van Dam et al., 2001; Dinópolis Foundation, 2008). However, the geographic and stratigraphic location of the paleontological sites is generally poorly defined in many cases, especially when mammal remains have scarce paleontological or biostratigraphic interest.

The paleontological studies have catalogued >150 fossil sites between Teruel city and Villalba Alta, but only 72 contain enough biostratigraphical significance and detailed stratigraphic information that permits to properly place them in our 3D stratigraphic framework. It has been possible to locate 69 sites, mainly thanks to the works by Weerd (1976), Mein et al. (1983, 1990), Adrover et al. (1986), Alcalá et al. (1994), and van Dam (1997), which provided valuable information on the geographic location (map, geographic coordinates), geological information (description of the vertical succession, mapping, geological cross-sections) or sketches and photographs of the mammal sites. In addition, three macro-mammal sites (CO-1, CO-2 and VAG) were recently located and dated by Ezquerro (2017). Despite knowing their location with respect to our stratigraphic profiles Masada del Valle, El Arquillo, La Gloria, Celadas, Puente Minero and Los Aguanaces, other paleontological sites far away from biozone limits have not been used because they would not improve the chronological model.

Table 1 compiles the acronyms (code), name, and reference works of the above mentioned 72 mammal sites used in this work, as well as valuable information on its stratigraphic location. The position of each mammal site in the corresponding stratigraphic profile is shown in the correlation panels (Supplementary Figs. 1 to 9). The sites have been ordered in Table 1, according to their assignment to the MN zones (MN9 to MN 17) and, within each zone, based on the relative position with respect to stratigraphic correlation levels.

Despite most mammal sites could be framed within our 3D stratigraphic model, some open questions related to their nomenclature and MN zone assignment remain unresolved. Next, we discuss these cases. Regarding the nomenclature, sites ORR (Weerd, 1976) and OR1 (Adrover, 1986; Mein et al., 1990) could be the same, as suggest van Dam et al. (2006). However, after reviewing the locations, stratigraphic columns and schemes, we have considered that they are different sites,

since clear differences in their location and stratigraphic position do exist. ORR is located in the central part of a thick limestone package near Casas del Río, while OR1 is located in a marl level under such limestone package at the Orrios road, south to the former one. As a second case, the nomenclature of fossil sites used by Weerd (1976) in the Escorihuela area differs from that of later works, which generates confusion (e.g., Opdyke et al., 1997; van Dam, 2006; Rodríguez-López et al., 2012). We have chosen the nomenclature by Mein et al. (1990), since is the most followed one.

In other cases, the same fossil site could have been cited with different names by different authors. The two sites (CO-1 and CO-2 in Table 1), discovered by Ezquerro (2017) in El Coscojar area, southwards of Escorihuela village, provisionally indicating a MN15 zone (Alcalá, *pers. com.*), could correspond to the Colmenar micro-mammal site, Ruscinian in age (zone MN15), described by Mein et al. (1983). Although the latter has not been accurately located, the proximity of the Colmenar ravine (< 100 m) and their similar age could indicate that they are the same fossiliferous beds indeed. In the same way, the site Villalba Alta Granja (VAG in Table 1; Ezquerro, 2017) is located in a bed extending laterally >200 m in Villalba Alta village. A provisional study of the macromammal teeth and other bones indicates a Ruscinian age (zone MN15, Alcalá, *pers. com.*) that is consistent with the nearby micro-mammal sites described by Mein et al. (1990).

Regarding the age assigned to the sites, some uncertainties have been also found. The Peralejos D site was originally included in the *Progonomys hispanicus* zone (MN10) by Weerd (1976), was then assigned to the *Parapodemus lugdunensis* zone (MN11) by van Dam (1997) and van Dam et al. (2001), local zone K, and later again assigned, to a new local area J4 (MN10) by van Dam et al. (2006), from the entry of *Parapodemus lugdunensis* to the entry of *Huerzelerimys vireti*. In this case, we retain the ascription of this site to the MN10 zone. The sites Poblado Ibérico and Orrios 3 were originally attributed to the *Miomys stehlini* zone (MN16a) by Mein et al. (1983) and Adrover et al. (1986), but then assigned to the *Dolomys* zone (MN15b) by the presence of *Miomys occitanus* and *Stephanomys vandeweerdii* (Mein et al., 1990), which do not go through the MN16 zone. The same happens with La Gloria 4, Orrios 1, Peralejos F and Celadas 6 sites, assigned to the *Trilophomys* zone, originally attributed to MN15a (Mein et al., 1983; Adrover, 1986), and then to MN14 (Mein et al., 1990). In these last cases, the new age proposed, also assumed by other researchers, are followed in this work.

6. Magnetostratigraphic constraints: Estimating the age of the guide levels

6.1. Magnetostratigraphy of the lower part of the sedimentary record

The lower part of the infill was initially studied by Krijgsman et al. (1996) in three magnetostratigraphic sections (*La Roma*, *La Gloria* and *El Bunker*) with the aim of calibrating the boundaries of the mammal zones. The first profile is located in the centre of the study area (west of Peralejos village), and the other two in the southern part (Los Mansuetos area, east of Teruel city).

La Gloria section of Krijgsman et al. (1996) coincides with the lower half of our El Enebral (Te-5) stratigraphic profile (Teruel transect) (Supplementary fig. 1). The Local Polarity Sequence (LPS) anchoring was based on the AG 4 (MN10) and AG 7 (MN11) sites, which are located at the upper part of the succession. The wide normal polarity chron at the base of this section corresponds to C5n, and, therefore, the normal chron located in the upper part would probably correspond to C4An (Krijgsman, 1996; Krijgsman et al., 1996). These authors interpreted the lack of record correlative to C4Ar.1n subchron, which was attributed to low density of sampling and poor definition, or absence of the C4Ar.2n and C5n.1n subchrons (justified by later superposition of an opposite magnetic component). Kruvier et al. (2003) resampled a 24 m-thick interval in *La Gloria* section (with a density of one specimen each 0.1 m) comprising from the top of C5n.1n to the middle of C4An, which

Table 1

Most relevant biostratigraphic data of the northern Teruel Basin. See explanation in the text. References (number in parenthesis after the site name): 1– Weerd (1976); 2– Mein et al. (1983); 3– Adrover et al. (1986); 4– Mein et al. (1990); 5– Alcalá et al. (1994); 6– van Dam et al. (2001); 7– Alcalá et al. (2005); 8– Dinópolis Foundation (2008); 9– Ezquerro et al. (2012); 10– Alcalá (com. pers. 2016); 11– Ezquerro (2017). * Stratigraphic location, MN zone assignation and numerical age are incongruent.

PALEONTOLOGICAL SITE		MN ZONE		LOCAL ZONE	STRATIGRAPHIC AND MAGNETOSTRATIGRAPHIC LOCATION				
Code	Name (works of reference)	MN	Guide fossil	Name	Profile	Stratigraphic position with respect to correlation levels	Magnetostratigraphic position & profile	Cat.	Age
ROM 3	Masía La Roma 3 (6)	9	<i>Progonomy cf. hispanicus</i>	I	Pe-5	< 1 m below L2a		2	9.78
ROM 4	Masía La Roma 4 (6)	10	<i>Cricetulodon Progonomys hispanicus</i>	J1	Pe-5	between L2a and L6 (50 m) 3 m above L2a	C4Ar (lower part) La Roma	1	9.56
ROM 7	Masía La Roma 7 (6)			J1	Pe-5	between L2a and L6 (50 m) 8 m above L2a	C4Ar (middle part) La Roma	1	9.44
MBB	Masada del Barbo 2B (1, 5, 6, 8)			J2	SB-8	28 m below L6	C4Ar.2r (top part) Masada Ruea	1	9.37
PER A	Perales A (1)			J2	Pe-6	between L2a and L6 (49 m) 16.5 m above L2a		2	9.21
ROM 11	Masía La Roma 11 (6)			J2	Pe-5	between L2a and L6 (50 m) 17 m above L2a	C4Ar (upper part) La Roma	1	9.16
MR 604	Masía La Roma km.604 (7)			–	Al-5	31 m below L5a 41 m below L6		3	9.08
AG 4	Los Aguanaces 4 (2, 3, 4, 5, 8)			J3	Te-5	1 m below L3	C4An, La Gloria	1	9.04
PER B	Perales B (1)			J3	Pe-6	between L2a and L6 (49 m) 20 m below L6		2	8.95
MRU	Masada Ruea (6, 8)			J3	SB-8	13.5 m below L6	C4An, Masada Ruea	1	8.84
PER C	Perales C (1)			J3	Pe-6	between L2a and L6 (49 m) 12.5 m below L6		2	8.80
PER D	Perales D (1)			J4 - K	Pe-6	between L2a and L6 (49 m) 8.5 m below L6		2	8.74
ALF	Alfambra (1, 6, 8)	11	<i>Parapodemus lugdunensis</i>	K	SB-8	11.5 m below L6	C4r (base) Masada del Valle	1	8.66
AG 7	Los Aguanaces 7 (6, 8)			K	Te-5	5 m above L3 25 m below L6	C4r (prob. C4r.1r) La Gloria / El Bunker	1	8.50
BUN 6	El Bunker 6/7 (6, 8)			K	Te-5	1.5 m below L6	C4n (base) El Bunker	1	8.01
MRU 2	Masada Ruea 2 (6, 8)			K	SB-8	4 m below L6		2	7.99
TO A	Tortajada A (1, 6, 8)			K	SB-7	2 m below L6		3	7.93
ALJ	Los Aljezares (2, 3, 4, 5, 8)	12	<i>Parapodemus gaudryi barbarae</i>	L	Te-4	1 m below L6		3	7.87
MRU 3	Masada Ruea 3 (6)			L	SB-8	1.5 m above L6		2	7.82
BC	Barranco de las Calaveras (1, 2, 4, 5, 8)			L	SB-6	between L6 and L9 (77 m) 3 m above L6		3	7.75
LP	Las Pedrizas (1, 2, 4, 5, 8)			L	SB-6	between L6 and L9 (77 m) 13 m above L6		3	7.70
TO B	Tortajada B (1, 6, 8)			L	SB-7	between L6 and L9 (69 m) 8 m above L6		3	7.65
MRU 4	Masada Ruea 4 (6)			L	SB-8	6 m above L6		2	7.61
VB 2	Villalba Baja 2 (1, 6, 8)			L	To-3	48 m below L9		3	7.44
KS 2	Las Casiones 2 (6, 8)			L	To-1	6.5 m below L7 (top of Par1)		3	7.40
TOC-D	Tortajada C—D (6, 8)			L	SB-7	between L6 and L9 (69 m) 15 m above L6		3	7.31
C3P	Cueva de las 3 puertas (8)			–	Te-4	between L6 and L9 (28 m) 10 m above L6		2	7.30
CG	Cerro de La Garita (1, 2, 4, 5, 8)			L	SB-6	between L6 and L9 (77 m) 26 m above L6		3	7.11
LM	Los Mansuetos (1, 4, 5, 8)			L	Te-4	between L6 and L9 (28 m) 8 m below L9		2	7.05
MDV 7	Masada del Valle 7 (1, 6)	13		M1	SB-8	11 above L6		2	6.88
BUN	El Bunker (5, 8)		<i>Sthephanomys ramblensis</i>	M1	Te-5	between L6 and L9 (35 m) 10 m above L6	C4n (middle) El Bunker	1	6.49
VB 1	Villalba Baja 1 (1)			M	To-2	between L7 and L9 (43.5 m) < 1 m above L7		3	6.45
MOD	Las Modorras (6)		<i>Occitanomys adroveri</i>	M	Ce-6	5.5 m above L7		3	6.33
KS	Las Casiones (5, 6, 8)		<i>Apodemus gudrunae</i>	M2	To-1	between L7 and L9 (19 m) 3.5 m above L7 15.5 m below L9		3	6.28
LV	Los Valles (2)			–	Pe-4	8 m above L6		3	6.27
KSS	Las Casiones Superior (6, 8)			M2	To-1	between L7 and L9 (19 m) 5 m above L7 (14 m bel. L9)		3	6.22
BUN 5	El Bunker 5 (6)			M1	Te-5	between L6 and L9 (35 m) 7 m below L9	C4n (uppermost) El Bunker	1	6.06
CAP 3	El Capón 3 (6, 11)			M	Al-5	between L7a and L9 (8.5 m) (L6-L9: 21.5 m) 3 m below L9		3	5.68
MIL	Los Milagros (4, 5, 8)			M2	Te-4	1.5 m below L9		3	5.15

(continued on next page)

Table 1 (continued)

PALEONTOLOGICAL SITE		MN ZONE		LOCAL ZONE	STRATIGRAPHIC AND MAGNETOSTRATIGRAPHIC LOCATION				
Code	Name (works of reference)	MN	Guide fossil	Name	Profile	Stratigraphic position with respect to correlation levels	Magnetostratigraphic position & profile	Cat.	Age
CE 8	Celadas 8 (2)	14	<i>Celadensia</i>	Ce	Ce-1	3 m below L9		3	5.03
LC 3	Loma de Casares 3 (4)			Ce	Ce-2	<1 m below L9		2	4.99
PER E	Perales E (4, 5)			–	Pe-8	between L7 and L9 (38 m)		3	4.96
LC 2	Lomas de Casares 2 (4)			Ce	Ce-2	1.5 m below L9			
CE 5	Celadas 5 (2)			2P	Ce-1	5.5 m above L9		3	4.84
GLO 4	La Gloria 4 (5, 6, 8)			–	Te-5	9 m above L9		2	4.71
CE 6	Celadas 6 (2)	15	<i>Promimomys</i> <i>Paraethomys</i> <i>Trilophomys</i>	Tr	Ce-1	10 m above L9		2	4.54
OR 1	Orrios 1 (4)			–	Or-3	19 m above L9		2	4.42
						5 m below L10	C3n.1r (middle part) Orrios	1	4.40
PER F	Perales F (4)			–	Pe-8	12 m above L9		3	4.34
ORR	Orrios (1)			–	Or-3	between L10 and L11 (9 m)	C3n.1n (base) Orrios	1	4.27
						4 m above L10			
LC 1	Lomas de Casares 1 (4)	15	<i>Mimomys archaicus</i>	–	Ce-2	27 m above L9		3	4.25
VAR 1	Villalba Alta Río 1 (4)			Tr	Vi-1	3 m below L11	C3n.1n (top) Villalba Alta Río	1	4.20
VAL	Villalba Alta (3)			aM	Vi-2	6 m below L11		2	4.19
VAR 2	Villalba Alta Río 2 (4)			aM	Vi-1	< 1 m below L11	C2Ar (base) Villalba Alta Río	1	4.12
VAR 3	Villalba Alta Río 3 (4)			aM	Vi-1	between L11 and L12 (8 m)	C2Ar (lower part) Villalba Alta Río	1	4.03
VA 1	Villalba Alta 1 (4)			aM	Vi-2	3 m above L11		3	4.01
CO-1	El Coscojar 1 (10,11)	16	<i>Mimomys archaicus</i>	–	Al-9	between L11 & L12 (14 m)		2	3.84
						5 m below L12			
						between L11a & L13 (9 m)			
						2.5 m above L11a			
						6.5 m below L13			
						< 1 m below L12	C2Ar (middle) Villalba Alta Río	1	3.81
VAR 4	Villalba Alta Río 4 (4)	16	<i>Dolomys</i>	Do	Vi-1	between L9 & L13te (15 m)		2	3.78
PI	Poblado Ibérico (2, 4, 8)			–	Te-2	5 m below L13te		1	3.77
EB	Escorihuela B (1, 2, 4)			Do	Al-12	just below L13	C2Ar Escorihuela	1	3.70
OR 3	Orrios 3 (3)			Do	Or-3	between L11 & L19 (49 m)	C2Ar (mid-upper part) Villalba Alta Río	1	3.70
CO-2	El Coscojar 2 (10, 11)			–	Al-9	1.5 m above L11		2	3.69
VAG	Villalba Alta Granja (10, 11)			–	Vi-2	3 m above L13		2	3.61
VA 5*	Villalba Alta 5 (4)	16	<i>Mimomys archaicus</i>	–	Vi-1	7 m above L12			
						just L14	C2An.3n (lower part) Villalba Alta	1	3.58*
EC*	Escorihuela C (1, 2, 4)			MM	Al-12	between L13 and L18 (48 m)	C2Ar-C2An.3n (limit) Escorihuela	1	3.59*
OR 5	Orrios 5 (1, 2, 4)			–	Or-5	6 m above L13		3	3.56
EA	Escorihuela A (1, 2, 4)			MM	Al-12	just L14o			
						7 m above L11			
LG 0	La Guea 0 (2, 4, 8)	16	<i>Mimomys cf. polinicus</i>	Ki	Al-12	between L3 and L18 (48 m)	C2An (base) Escorihuela	1	3.48
CcE 1	Concud Estación 1 (2, 4, 8)			Ki	SB-2	13 m above L13		2	3.16
LG 1	La Guea 1 (2, 4, 8)			Ki	SB-2	between L14s & L20 (64 m)		1	2.87
OR 8	Orrios 8 (2, 4)			–	Or-6	25 m above L14s		2	2.78
CcE 2	Concud Estación 2 (2, 4, 8)			Ki	SB-3	21.5 m below L20	C2An Concud	1	2.66
						between L14s & L20 (64 m)		1	2.54
						20 m below L20			
						4 m above L18			
						1.5 m below L20	C2r Concud	1	2.54
RTC	Rotonda Teruel Centro (9)	17	<i>Equus stenonis</i>	–	SB-5	Top of synrift sequence	8 m above C2An C2r.1r Masada Cociero	1	1.95

includes the MN10-MN11 boundary (Fig. 5). Based on the instability of the Natural (NRM) and Characteristic (ChRM) Remnant Magnetizations, they concluded that hydromorphism processes could have controlled a subsequent remagnetization in the upper part, and advised that the section should not be used for chronological purposes, giving low reliability to the previously established age. The physical correlation between El Bunker and La Gloria magnetostratigraphic sections reduces the uncertainty, being the guide levels and the key paleontological sites located in well-defined polarity zones. Our guide levels 1, 2 and 3 have been recognized within this magnetostratigraphic section, being located, respectively, in C5n (top part), C4Ar (lower part), and C4An (middle part) chrons (Fig. 6).

La Roma section was sampled by Krijgsman et al. (1996) with quite high density (approximately one specimen per metre), resulting in a very acceptable resolution for the definition of chrons. This section correlates with the basal part of our Rambla de la Covacha profile (Pe-5; Perales Transect, see Supplementary fig. 5), while mammal sites confirm MN9 (site ROM 3) and MN10 (ROM 4, 7 and 11) zones. Krijgsman et al. (1996) related the LPS with C4Ar and C4An chrons, stating that the low intensity (poor signal) of samples in the middle part of the profile had probably prevented the record of C4Ar.1n (Fig. 5). Local guide level 2a is located approximately in the basal part of this magnetostratigraphic section (beginning of C4Ar; probably C4Ar.3r subchron), which is coherent with the location of the guide level 2 in the

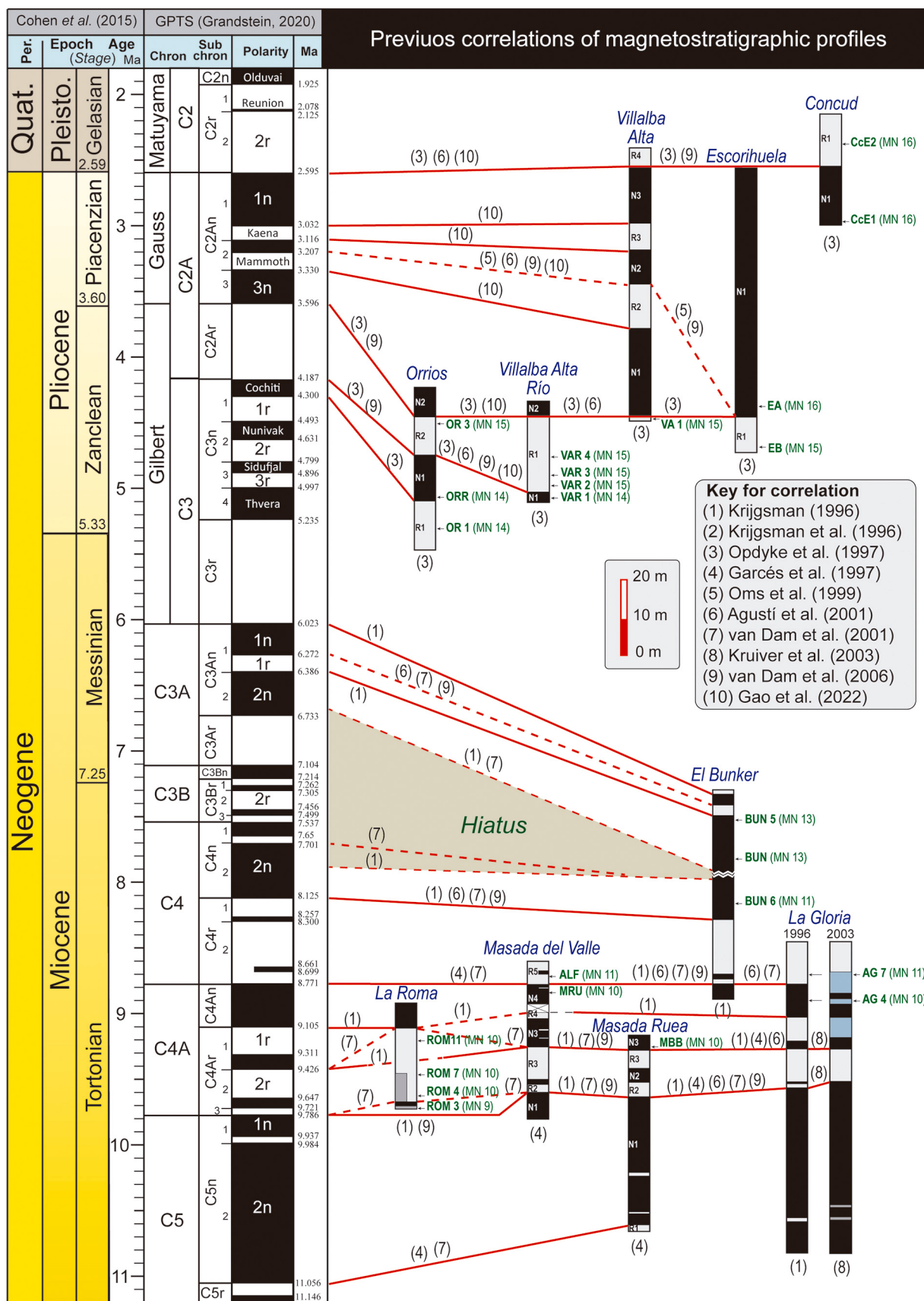


Fig. 5. Compilation of previous magnetostratigraphic sections and their correlations in the northern sector of the Teruel Basin. Names and MN zones or mammal sites used for dating are in green colour. See explanation in the text. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

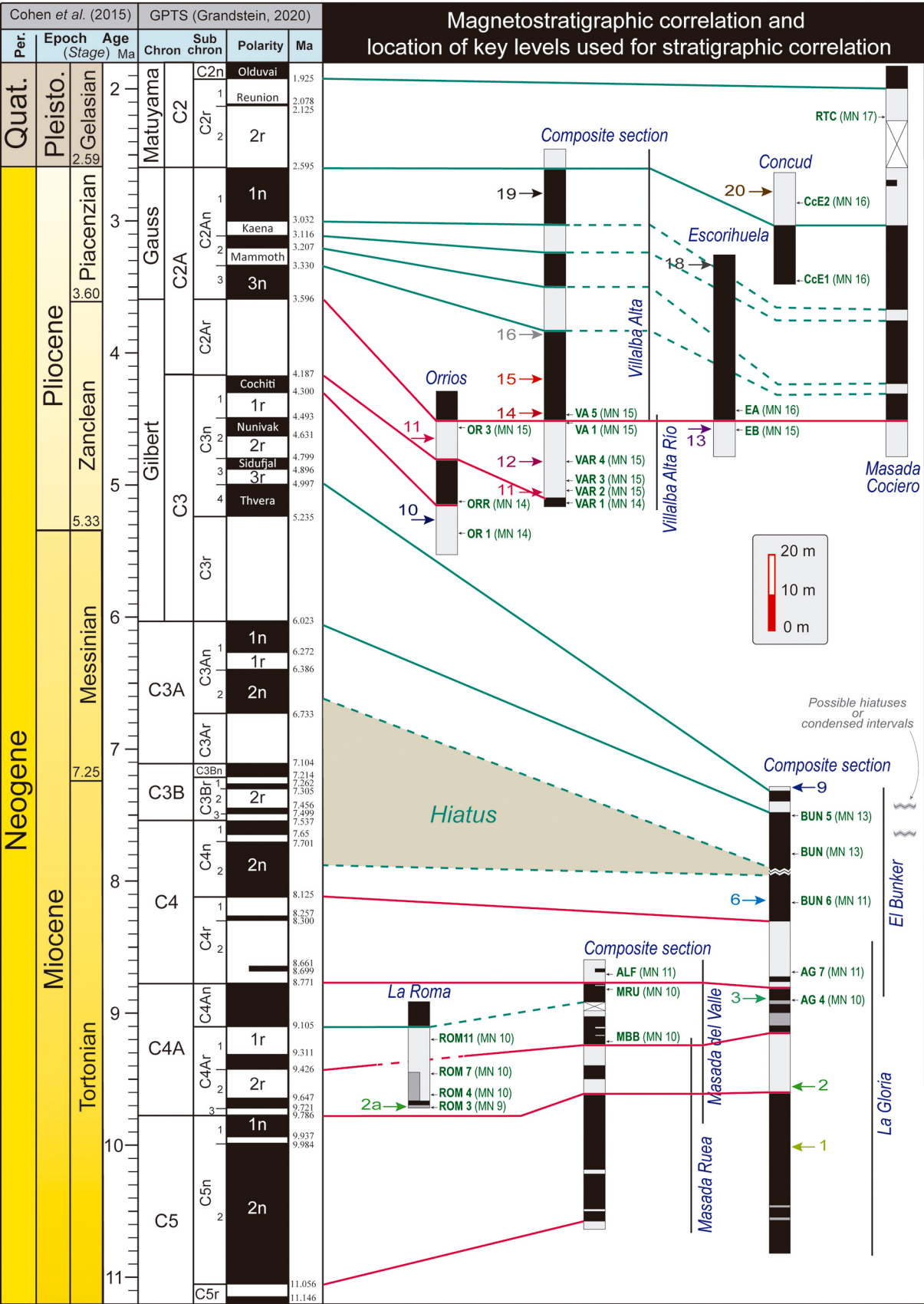


Fig. 6. Composite magnetostratigraphic sections and correlation proposed in this work. Coloured numbers and arrows correspond to the position of the guide levels. Note the new correlation (blue lines) in comparison with the previous interpretations showed in Fig. 5. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

lowermost part of a reverse chron (C4Ar) in the La Gloria - El Bunker composite section (Fig. 6).

Based on mammal fauna belonging to MN11 (BUN 6–7 sites) and MN13 (BUN and BUN 5 sites) zones, Krijgsman et al. (1996) correlated the LPS basal normal chron in the *El Bunker* section (Figs. 2, 5) with the C4An chron, and the second normal chron with C4n.2n. The distribution and ages of the fossil sites in this section, and especially the absence of MN12 fauna, suggest an important change in sedimentation rate or a hiatus at the upper part of the section. Krijgsman et al. (1996) used the same reasoning to explain this uncertainty and propose drive out this part of the local scale and extend the MN11 zone to the lower part of C4n.2n. Garcés et al. (1999) suggested that the temporal lapse for the hiatus comprises from the base of C4n.1r to the top of C3Ar chrons (Fig. 5) and a certain diachrony of the MN11-MN12 boundary. They ascribed the younger normal chron of the section to C3An.1n. El Bunker section has been correlated with the upper half of our stratigraphic profile El Enebral (Te-5; Supplementary fig. 1). This correlation has allowed locating guide levels 3 and 6 at the C4An and C4n (lower part) chrons, respectively. It has also confirmed that the lower part of El Bunker section broadly overlaps with the upper part of La Gloria section, as proposed by van Dam et al. (2001), allowing defining the La Gloria-El Bunker composite magnetostratigraphic section. The correlation allows minimizing a low-definition interval described by Krüvier et al. (2003) in La Gloria section (Fig. 6). Furthermore, the upper part of El Bunker section has been reinterpreted, now covering a longer time interval between C3An.1n and C3n.3r (Fig. 6). This reinterpretation has been based on the position of guide level 9 at the top of the El Enebral (Te-5) profile. With respect to the interpretation by van Dam et al. (2001), who strictly attributed that upper part to MN13 (C3r), the local magnetozone has been extended to the first reverse chron that corresponds to MN14. As we explain below, it has been possible to assign the guide level 9 to the MN14 zone in a large area of the basin (e.g. Celadas transect; see Supplementary Fig. 4). The reinterpretation also could be solved assuming several minor hiatuses or condensed intervals in the C3An and C3r chrons, which is not supported by the available data.

Subsequently, Garcés et al. (1999) performed the magnetostratigraphic sections of *Masada Ruea* and *Masada del Valle*, which are located immediately to the north of Teruel city (San Blas Transect; see Supplementary fig. 2). The sampling presented a fairly good resolution (one specimen every 0.5 to 1 m). From both sections, they built a composite section, correlating and interpreting the limit between a wide normal and the subsequent reverse chron as the C5n-C4Ar limit (Fig. 5). The reverse-normal polarity change at the base of the *Masada Ruea* section is correlated with the C5r-C5n limit, while the normal-reverse change in the top of the *Masada del Valle* section is attributed to the C4An-C4r limit. Following Krijgsman (1996) and Krijgsman et al. (1996), they also locate the MN10-MN11 boundary in the upper part of C4An (Fig. 5). Based on the little thickness between Alfambra (ALF) and *Masada del Valle* 7 (MDV7) sites in the *Masada del Valle* section, they also propose a possible hiatus above its R5 chron that would correspond partially to C4r. The first interpretation of these sections by van Dam (1997) and Garcés et al. (1999) was partially reinterpreted by van Dam et al. (2001), who correlated the local normal chron (N3) of *Masada Ruea* and *Masada del Valle* with the top of the La Roma and La Gloria sections, so that in these last two profiles the assignment of N3 changed from C4An to C4Ar.1n (Fig. 5). The local N4 chron of *Masada del Valle* was moved in turn from C4r.2n to C4An, disappearing a normal excursion in the R5 local chron. These changes with respect to the correlation by Krijgsman (1996), Krijgsman et al. (1996), van Dam (1997) and Garcés et al. (1999) were based on: (i) the reinterpretation of a sample in the middle part of the La Gloria section (ii) the inclusion of a reverse subchron towards the top of the younger normal chron in El Bunker section based on a single-site (see Garcés et al., 1999; van Dam et al., 2001), and (iii) a normal sample of the top of the *Masada del Valle* section (local chron R5) that also seems to have been reinterpreted.

Stratigraphical correlation of the *Masada Ruea* and *Masada del Valle*

magnetostratigraphic sections with our Cerro de los Aldabades I stratigraphic profile (SB-8, Supplementary fig. 2) is more in agreement with the magnetostratigraphic correlation previously carried out between both profiles by Garcés et al. (1999), and has been maintained here (Figs. 6 and 7). Moreover, the stratigraphic correlation of the *Masada Ruea-Masada del Valle* composite section with that of the La Gloria-El Bunker avoids losing temporal control and maintaining the definition of the C4Ar.1n-C4Ar.1r and C4An-C4r limits (Fig. 7). The location of the guide level 6 in the SB-8 profile (Supplementary fig. 2), ~ 6 m above the top of the magnetostratigraphic section, also reinforces the correlation between both composite sections.

6.2. Magnetostratigraphy of the upper part of the sedimentary record

The magnetostratigraphy of the upper part of the sedimentary succession of this basin was initially studied by Opdyke et al. (1997) from five sections (Fig. 5): Concul Station (or Concul), Orrios, Villalba Alta, Villalba Alta Río and Escorihuela. With the exception of the first one, located west of Teruel city, the other four sections are located in the northernmost part of the basin (Fig. 2). In order to define the chrons, samples with optimal demagnetization parameters were only considered by the authors (class I), which led to a low-density sampling in many cases (normally one sample each 2.5 m, with intervals up to 6 m between specimens in the Concul section).

Based on the biostratigraphical constraints imposed by MN14 sites (OR1, ORR and VAR 1) and MN15 sites (OR3 and VAR 2, VAR 3 and VAR 4), Opdyke et al. (1997) correlated the LPS in Orrios and Villalba Alta Río with the C3n (upper part), C2Ar and C2An (basalmost part) chrons; the Orrios section also records the C3n.1r subchron (Figs. 5 and 6). These authors located the MN14-MN15 boundary at the top of the first normal chron in both sections, that is, the C3n.1n chron (Cochiti subchron, Figs. 5 and 6). With the proposed correlation, the C2Ar-C2An limit is located at the top of the Orrios and Villalba Alta Río sections (Fig. 5). Our Los Tollos profile (Or-3; Supplementary fig. 7) was logged at the same location as the Orrios magnetostratigraphic section, so that the stratigraphic correlation can be considered as robust. This allows locating our guide levels 10 and 11 in the C3n.1r (upper part) and C2Ar (middle part) chrons (Supplementary notes 2).

The Villalba Alta section corresponds with a long record in which seven magnetozones have been distinguished (Fig. 5). The VA1 fossil site (MN15) is located very close to the lowermost change of polarity (from reverse to normal) in the LPS. This change was interpreted by Opdyke et al. (1997) as representing the C2Ar-C2An limit, extending the section to the basalmost part of C2r (Fig. 5). The youngest polarity change (C2An-C2r limit; Gauss-Matuyama) would be located at the top of the section. Thanks to the stratigraphic correlation with our Los Aliagares profile (Vi-1; Supplementary fig. 8), the vertical correspondence of the Villalba Alta Río and Villalba Alta magnetostratigraphic sections has been strengthened. This stratigraphic correlation reinforces the magnetostratigraphic correlation initially made by Opdyke et al. (1997) between both sections, which has been later assumed by other researchers who already used them as a composite section (e.g., Agustí et al., 2001). This composite section has been key for characterizing the age of the upper part of the sedimentary succession in the Teruel Basin, since six guide levels (11, 12, 14, 15, 16, and 19) could have been located within the LPS (Fig. 6): levels 11 and 12 are situated at the base and middle part, respectively, of the C2Ar chron; levels 14, 15 and 16 are placed at the base, centre and top of the C2An.3n subchron, respectively; level 19 is located in the middle part of the C2An.1n subchron.

The only polarity change recognized in the Escorihuela section (Fig. 5) was interpreted by Opdyke et al. (1997) as being the limit between the C2Ar (Gilbert) and C2An (Gauss) chrons. This assumption was based on the biostratigraphic data obtained immediately below (EB site; MN15) and above (EA sites; MN16) this limit. Consequently, the boundary between zones MN15 and MN16 was located very close to the chron change, and the authors preferred to make both coincide (see Fig. 5).

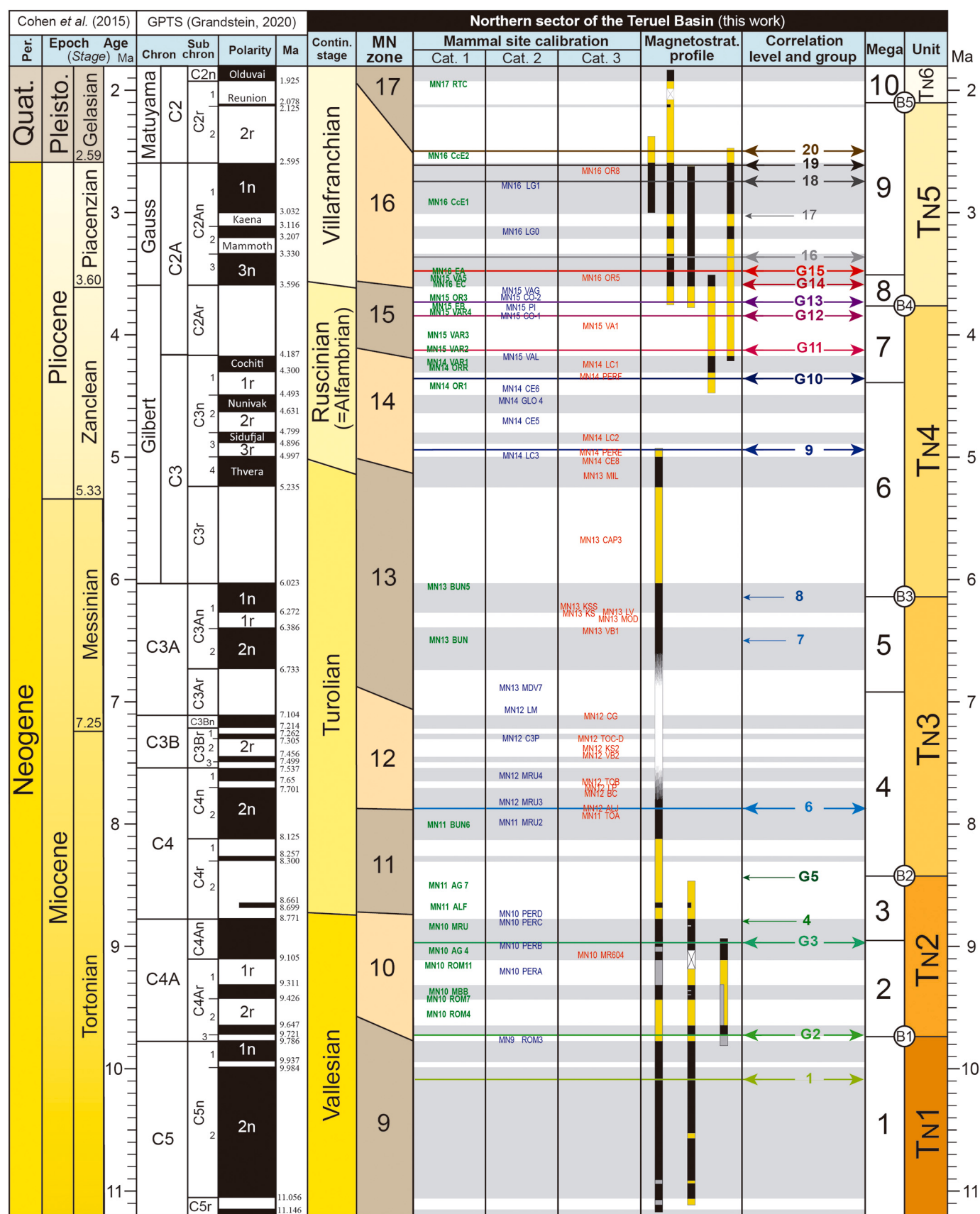


Fig. 7. Bio-chronostratigraphic chart for the northern Teruel Basin showing the reviewed bio- and magnetostratigraphic data and their integration with the new stratigraphical framework.

Then, Oms et al. (1999) and van Dam et al. (2006) proposed a new interpretation relating that polarity change to the limit between C2An.2r (Mammoth) and C2An.2n. This magnetostratigraphic section coincides with our Loma de la Poveda profile (Al-12; Supplementary fig. 6), and the stratigraphic correlation supports the previous interpretation by Opdyke et al. (1997). This section has allowed locating the guide level 13 in the C2Ar chron (upper part) and the level 18 in the C2An chron (Fig. 6).

Among the many possibilities that they suggested, Opdyke et al. (1997) interpreted the polarity change recognized in the *Concud Station* section as representing the C2An-C2r limit (Gauss-Matuyama). This interpretation was based on the MN16 fauna located above and below it (CcE1 and CcE2 sites, respectively) and on the location of MN16-MN17 boundary within the C2r chron but closer to C2n (Olduvai subchron) in other Iberian basins. This profile comprises the middle-upper part of our Concud profile (SB-3, Supplementary fig. 2), and has allowed locating the guide level 20 into the C2r chron (Fig. 6).

A new magnetostratigraphic section in the Masada Cociero profile (SB-5; Supplementary fig. 2) (Ezquerro et al., 2016; Ezquerro, 2017) that has been anchored in order to include the Rotonda Teruel Centro (RTC)

mammal site, with MN17 fauna in its upper part (Fig. 6) has been stratigraphically correlated with the Concud Station section of Opdyke et al. (1997) and with the GPTS of Ogg (2012) and Gradstein et al. (2020). The LPS of the *Masada Cociero* section records eight magnetozones, the C2r-C2n limit has been recognized at the top of the profile, and the C2Ar-C2An limit (Gilbert-Gauss) towards the base (Fig. 6).

7. Chronostratigraphic model: integrating lithostratigraphy, biostratigraphy and magnetostratigraphy

As mentioned above, stratigraphy and paleontology have always been closely interrelated in the Teruel Basin, although paleontological interest has apparently prevailed. Here, we integrate the bio- and magnetostratigraphic data in a well-defined 3D stratigraphic architecture (see Supplementary notes 2 and figures) in order to refine the chronostratigraphy and the calibration of the MN zone in this reference basin (Figs. 7 and 8). Physical correlation of guide levels and profiles has allowed anchoring the related bio- and magnetostratigraphic limits (Supplementary figs. 1 to 9) and precisely date the genetic units (Figs. 7 and 8). Integration of data has allowed the majority of the guide levels to

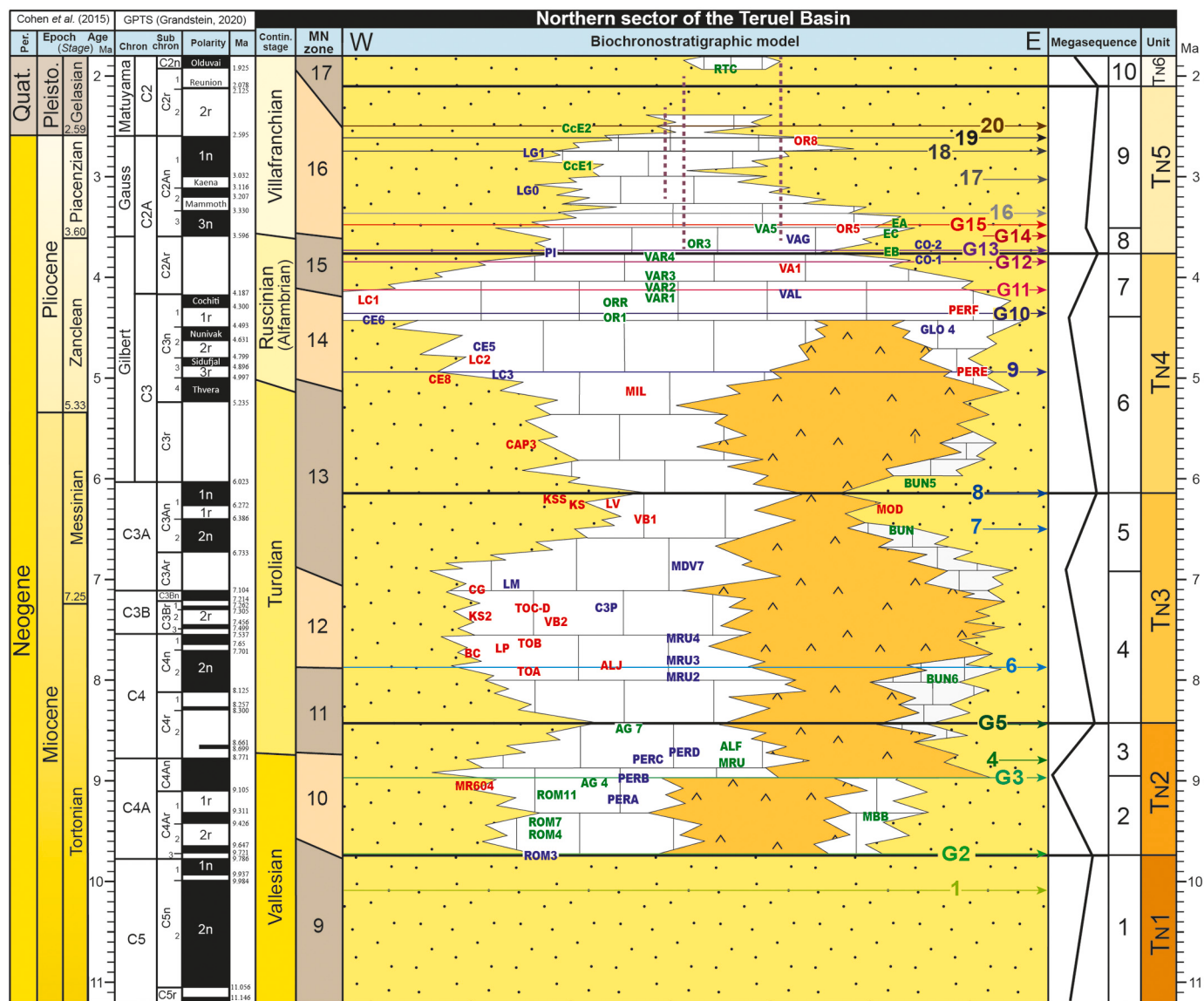


Fig. 8. Proposal of the bio-chronostratigraphic model for the northern Teruel Basin. Throughout the longitudinal axis of the basin, carbonates or gypsums can be absent towards the margins (see Supplementary Figures), where each one grades into detrital facies directly. The carbonates arrangement in TN5 and TN6 is partially established from wells (vertical dashed lines), varying in the north and south zones.

be correlated with the Local Polarity Series (LPS) and, in turn, with the Global Polarity Time Scale (GPTS) of Gradstein et al. (2020). This process has allowed constraining numerical ages for the correlation levels and building the chronostratigraphic model (Fig. 8; see Supplementary notes 2), that allows decreasing the age uncertainties of the MN zones and continental stage boundaries.

The mammal localities, previously assigned to MN zones and continental stages, have been ordered in each transect according to their relative position considering the available magnetostratigraphic information as well as the correlation levels (Supplementary Fig. 10). As previously stated, each locality has been given a qualitative value of credibility, for which three categories (1 to 3) have been established in descending order of accuracy (see section 3 and Table 1). The bio-chronostratigraphic chart of the basin (Fig. 7) has been built from merging the whole available information in each transect, but it is mainly based on the ages of category 1 sites. The vertical separation and age of fossil sites of categories 2 and 3 have been determined considering its relative position with respect to the correlation levels and the sedimentary thickness between them. In this sense, the vertical arrangement has been done carefully because variations in the sedimentation rate have been noted between different profiles and transects related to fault activity (Ezquerro, 2017). Subsequently, a direct interpolation between the position of these localities and the GPTS age has been made carefully.

In some cases, the time ordering of category 3 fossil sites assigned to the same mammal zone should be taken with caution, due to slight

uncertainties in their correlation (e.g. KS, MOD and LV assigned to MN13, in the Tortajada, Celadas and Peralejos transects, respectively; Figs. 7, 8 and Supplementary Fig. 10). In these cases, we consider more correct to use the laxer criterion of contemporaneity in the sense of Adrover et al. (1986) or Mein et al. (1990) referred to mammal sites located in the same MN zone with similar faunal associations. Previous absolute ages of the paleontological sites, based on direct interpolation with the magnetostratigraphy (assuming constant sedimentation rates) or on mathematical age models, have not been considered to establish our model. However, they will be revised and discussed in section 9.

8. The MN Zone boundaries: a review from the Teruel Basin

8.1. An overview

As in other continental basins, the temporal allocation of the MN zones and continental stages in the northern Teruel Basin has been changing through time, becoming more precise in parallel with biostratigraphic and magnetostratigraphic advances (Fig. 9). However, the use of different Geomagnetic Polarity Time Scales (GPTS), such as those by Cande and Kent (1995; CK95), Gradstein et al. (2004; G04), Lourens et al. (2004; GPTS04), Gee and Kent (2007; GK07), or Ogg (2012), for age calibration of the reference localities and the MN boundaries in the Teruel Basin and other Western European basins, has contributed to some ambiguity (see Supplementary table 1).

According to the existing literature, two stages can be distinguished

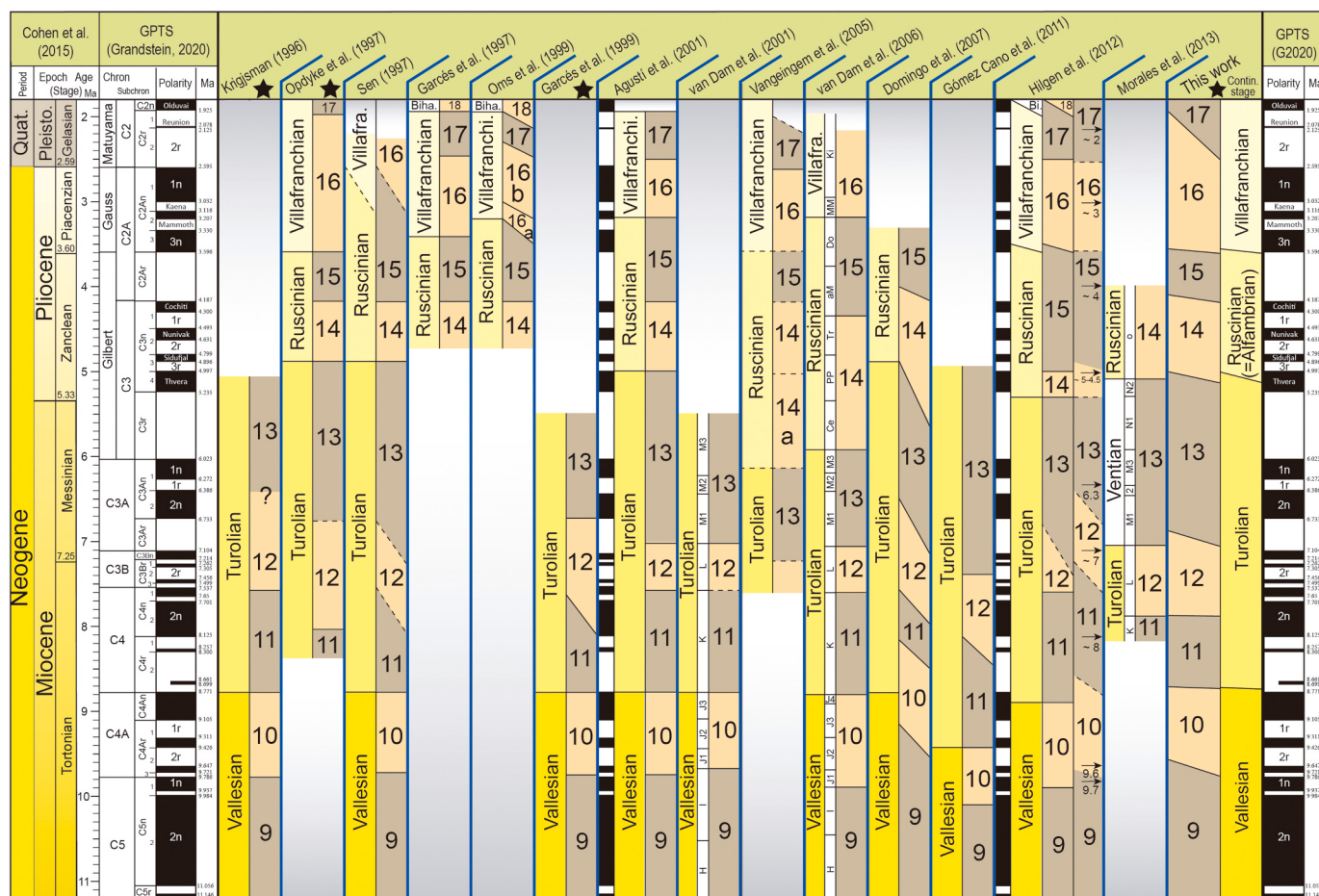


Fig. 9. Proposal of MN boundaries in the Teruel Basin derived from our work, compared with the boundaries previously established in the Teruel Basin (stars), other Iberian basins and Europe provinces. All of them have been calibrated to the GPTS of Gradstein et al. (2020) for enabling comparison. In Hilgen et al. (2012): MN units (left) as interval biochrons based on first and last historical appearances (their table 29.2) or (right) by reference localities after De Bruijn et al. (1992), with estimated ages (Azanza et al., 1997; Garcés et al., 1997; van Dam et al., 2006; Kálin and Kempf, 2009, among others).

in the process of building the chronostratigraphic model (Fig. 8). Firstly, the age of MN zones was calibrated through the anchorage of representative fossil localities with the GPTS in use by means of specific magnetostratigraphic studies. Early studies in the basin (Krijgsman, 1996; Krijgsman et al., 1996; Opdyke et al., 1997; van Dam, 1997; Garcés et al., 1999), and others with the same classical methodological approach that refined previous results, filled the gaps in the Neogene sequence or proposed correlation with other Spanish and European basins (Sen, 1997; Garcés et al., 1999; Oms et al., 1999; Agustí et al., 2001; van Dam et al., 2001; Vangengeim et al., 2005; Morales et al., 2013). Slight diachrony is assumed in some mammal zone boundaries (e.g. Sen, 1997; Oms et al., 1999), which arises in most cases because ages were estimated by combining data of different basins (Iberian or European). During this stage, age calibration of the MN zones did not change too much, as the MN boundaries were correlated with the magnetic polarity reversals, looking for simplicity (although some of the mammal sites are quite distant vertically from each other and from the chron limit itself; Figs. 5 and 9).

In a second stage, MN zone ages were calibrated based on quantitative age models that pursue to establish the absolute age of paleontological sites (van Dam et al., 2001, 2006; Domingo et al., 2007; Gómez Cano et al., 2011). In the majority of works, the ML AEO method (Alroy, 2000) is applied to faunal lists of a large number of localities from different basins in order to infer not only their relative order but also their absolute age. Table 2 compiles the age proposed for MN zones boundaries in several Spanish continental basins where this methodology was used with macromammals (90 sites from 17 basins; Domingo et al., 2007), and micromammals (93 sites, 18 basins; Gómez Cano et al., 2011). On the other hand, the site age database provided by van Dam et al. (2006), which links mammal turnovers with long-period astronomical forcing has also allowed the mammal zone ages to be calibrated. Age estimation in the latter case comes from different correlation methods, mammal sites positioned in magnetostratigraphic sections, biostratigraphical correlation with extrabasinal magnetostratigraphic or

radiometric dating, among others (for further detail see their Supplementary Table 1). In both methodological approaches (magnetostratigraphy or age modelling), the age uncertainty of a MN zone boundary ranges from the calibrated age of the last mammal site found in the lower zone to that of the first site in the upper zone.

Our bio-chronostratigraphic model adopts a similar approach to that of van Dam et al. (2006), but integrates stratigraphic, biostratigraphic and magnetostratigraphic information exclusively from the northern Teruel Basin. We next review the age of the boundaries of Late Miocene (Tortonian)–Early Pleistocene (Gelasian) mammal zones (MN 9/10 to MN 16/17) in the Teruel Basin and, as a result, that of the continental stages based on them. Some references to dating of MN zones in other Spanish basins will be included in order to frame the discussion. Therefore, and to facilitate comparison, in this work the magnetostratigraphic sections have been recalibrated according to the most recent GPTS by Gradstein et al. (2020).

8.2. The MN 9/10 (lower / upper Vallesian) boundary

This boundary is associated in the Teruel Basin with the entry of *Progonomys hispanicus* (Weerd, 1976; Mein et al., 1990). Based on the Torremormojón section in the Duero Basin (northern Spain), Krijgsman et al. (1996) and Krijgsman et al. (1996) positioned this boundary between C5n.1n (TM2 site) and C4Ar.2n (TM1 site), in the middle Vallesian (Fig. 9). Sen (1997) based on the magnetostratigraphic sections of Agustí et al. (1996) from the Can Llobateres site (Vallés-Penedés Basin, northeastern Iberia), slightly rejuvenated this limit to the transition between C4Ar.3r and C4Ar.2n. However, Garcés et al. (1999) and Agustí et al. (2001) maintained the previous age by Krijgsman (1996).

In addition, in order to propose new local mammal zones, van Dam et al. (2001) reinterpreted the correlation between the magnetostratigraphic sections in the lower infill of the Teruel Basin (Fig. 5), and modified previous proposals by van Dam (1997) and Garcés et al. (1999) eliminating the C4Ar.2n subchron in La Gloria and La Roma sections

Table 2

Ages proposed for the boundaries of the Upper Miocene-Pleistocene Mammal Neogene units (MN) in the northern Teruel Basin, based on integrated study of stratigraphic, biostratigraphic and magnetostratigraphic data, and comparison with previous works. Superscript numbers between parenthesis refer to basins in which the sites providing the numerical age constraints (lower and upper) are located: 1–Teruel, 2–Vallés-Penedés, 3–Cabriel, 4–Guadix-Baza, 5–Fortuna, 6–Calatayud-Daroca, 7–Duero, 8–Alicant North Prebetic, 9–Granada, 10–Duero, 11–Tagus, 12–Júcar, 13–Ebro, 14–Sarrión-Mijares. See text for details.

MN boundaries					
Boundary	This work Teruel Basin	Gómez Cano et al. (2011)	Domingo et al. (2007)	van Dam et al. (2006)	Agustí et al. (2001)
MN16-MN17	2.54–1.95		2.720 ⁽¹³⁾ –2.127 ⁽¹⁴⁾		2.5 ⁽⁴⁾
MN15-MN16	3.61–3.56		3.912 ⁽¹¹⁾ –3.297 ^(4,12)	3.21 ⁽¹⁾ –3.19 ⁽¹⁾	3.2 ⁽⁴⁾
MN14-MN15	4.20–4.12		4.186 ⁽¹⁾ –4.049 ⁽¹⁾	4.32 ⁽¹⁾ –4.15 ⁽¹⁾	4.2 ⁽¹⁾
MN13-MN14	5.15–5.03		5.689 ^(1,3,9,10) –4.825 ⁽⁸⁾	5.89 ⁽¹⁾ –5.79 ⁽¹⁾	4.9 ⁽³⁾
MN12-MN13	7.05–6.88	7.348 ⁽¹⁾ –6.847 ⁽¹⁾	7.011 ⁽¹⁾ –6.319 ⁽¹⁾	7.10 ⁽¹⁾ –7.00 ⁽¹⁾	6.8 (7.3) ⁽⁵⁾
MN11-MN12	7.93–7.87	8.462 ⁽¹⁾ –8.072 ⁽¹⁾	7.834–7.494 ⁽¹⁾	7.91 ⁽¹⁾ –7.60 ⁽¹⁾	7.5 (–7.9) ⁽³⁾
MN10-MN11	8.74–8.66	9.130 ⁽¹⁾	8.520 ⁽²⁾ –8.163 ⁽⁸⁾	8.80 ⁽¹⁾ –8.75 ⁽¹⁾	8.7 ⁽¹⁾
MN9-MN10	9.78–9.56	10.133 ^(6,10)	9.547 ⁽⁷⁾ –9.195 ⁽²⁾	9.94 ⁽⁶⁾ –9.87 ⁽¹⁾	9.7 ⁽²⁾
Local zone boundaries					
Boundary	This work Teruel Basin		van Dam et al. (2001)		van Dam et al. (2006)
MM-Ki	3.48–3.16				3.17–2.66
Do-MM	3.61–3.58				3.21–3.19
aM-Do	3.84–3.81				3.74–3.72
Tr-aM	4.20–4.19				4.32–4.15
2P-Tr	4.54–4.42				4.84–4.69
Ce-2P	4.84–4.71				5.35–5.26
M-Ce	5.15–5.03				5.89–5.79
L-M	7.05–6.88		6.8		7.10–7.00
K-L	7.93–7.87		7.9–7.5		7.91–7.60
J-K	8.74–8.66		8.7		8.80–8.75
I-J	9.78–9.56		9.7–9.6		9.94–9.87

(Fig. 7 of van Dam et al., 2001). As a result, they retained the coincidence of the MN 9/10 boundary with the top of C5n top, considering that this chron is represented at the base of La Roma section. However, the change of polarity recorded at the bottom of the La Roma section seems reversed to normal, the opposite to the expected (C5n/C4Ar) and the chron assignment does not match the estimated age either, considering constant sedimentation rate and interpolating the section position with respect to the CK95 scale, for the localities by van Dam et al. (2001). According to their data, the age of the MN 9/10 boundary could be bracketed between 9.7 Ma of Masía de la Roma 3 (MN9; local zone I) and 9.6 Ma of Masía de la Roma 4B (MN10; local zone J1). The ROM3 site is included in a younger chron, the C4Ar.3r, which is in accordance with its reverse polarity and the reverse to normal polarity change recorded at the base of the La Roma section.

After calibrating the age of Pedregueras 2C (MN9; Calatayud-Daroca Basin) and Masía de la Roma 4B (MN10; Teruel Basin) to GPTS04 (Table 2), van Dam et al. (2006) dated this boundary to 9.94–9.87 Ma (between the top of C5n.1r and the middle part of C5n.1n). However, the younger age seems unrealistic as the ROM4B site is positioned on a reverse chron (Krijgsman, 1996, p. 136).

Domingo et al. (2007) rejuvenated this boundary to 9.547–9.195 Ma (chrons C4Ar.2r to C4Ar.1r, respectively) based on the age of the Los Valles de Fuentidueña (MN9; Duero Basin) and Viladecavalls (MN10; Vallés-Penedés Basin) macromammal sites, using the CK95 scale for age calibration. In the same way, Gómez Cano et al. (2011), based on the age of micromammal fauna from Peralejos 5 (MN9) and Masía de la Roma 7 (MN10) calibrated with the GK07 scale, nearly similar to the CK95 one, bracketed this boundary between 10.244 and 10.049 Ma (C5n.2n chron) in the Teruel Basin. More precisely, considering their site age model, they positioned this boundary at 10.133 Ma, because MN9 (Pedregueras 2A D and Pedregueras 2C) and MN10 (Torremormojón 1 and Ampudia 1, both located in the Duero Basin) sites provided the same age (Table 2).

In our model for the northern Teruel Basin, the MN 9/10 boundary is located between 9.78 and 9.56 Ma, i.e., between the C4Ar.3r chron and the lowermost part of the C4Ar.2r chron on the GPTS of Gradstein et al. (2020). These ages have been estimated for the Masía de la Roma 3 (MN9) and Masía de la Roma 4B (MN10) sites, respectively (Table 1 and Fig. 9).

8.3. The MN 10/11 (Vallesian/Turolian) boundary

Considering Los Aguanaces 5B (MN10) and Los Aguanaces 7 (MN11) sites located in normal and reverse polarity sediments, respectively, in La Gloria section, Krijgsman (1996) and Krijgsman et al. (1996) positioned the MN10/11 boundary in the chron C4An (CK95), and estimated an age of 8.7 ± 0.1 Ma that also includes the C4r.2r chron. Later on, the boundary was corroborated by Sen (1997) at the top of C4An from the correlation of dated volcanoclastic ash in Greece and Iran, and later retained by Agustí et al. (2001) and van Dam et al. (2001, 2006) (Fig. 9). This boundary is placed by van Dam et al. (2006) in the C4An–C4r.2r transition, with an age of 8.80–8.75 Ma on the basis of the Cascante-Cubla 2 (MN10; local zone J4) and Patrimonio Forestal 5/5A (MN11; local zone K) sites of the southern Teruel Basin (Fig. 8 and Table 2). Domingo et al. (2007) rejuvenated this boundary to 8.520–8.163 Ma (between chrons C4r.2r and C4r.1r on the CK95 scale) according to the age of the Terrasa (MN10; Vallés-Penedés Basin) and Crevillente 2 (MN11; Alicante North Prebetic Basin) macromammal sites (Table 2).

In the same way, Gómez Cano et al. (2011), based on small mammals in the Teruel Basin, dated the boundary to 9.130 Ma (C4r.1r chron on the GK07 scale). In their model, they proposed a similar age for Peralejos C (MN10) and Peralejos D (MN11) sites, despite they overlap stratigraphically each other, both sites belong to the same mammal zone (see discussion chapter).

In this work, based on our stratigraphic correlation and the assignment proposed by Weerd (1976) and van Dam et al. (2001, 2006) for Peralejos D MN10 and Alfambra (MN11) sites, we locate the MN10/11

boundary between 8.74 Ma and 8.66 Ma (Fig. 9). Consequently, this boundary is positioned here in the lower part of C4r.2r in the GPTS of Gradstein et al. (2020).

8.4. The MN 11/12 boundary

Krijgsman (1996) and Krijgsman et al. (1996) located the MN11/12 boundary in the lowermost part of C4n based on the Cabriel Valley magnetostratigraphic section (Cabriel Basin, southern Iberia), and gave it an age of 7.5 ± 0.1 Ma based on CK95. Opdyke et al. (1997) proposed an older age, considering the fauna of Balneario (MN11) and Fuente Podrida (MN12) sites in the Cabriel Basin (southern Iberian Peninsula), and located the boundary in the base of C4n.2n (very close to C4r chron). After Sen (1997), the MN11/12 boundary is diachronic and the uncertainty threshold remains open, ranging between the limits established in the Cabriel Basin and those deduced in Turkey and Greece. Based on the last ones, supported by radiometric data, the boundary could be younger than the proposed by Opdyke et al. (1997), which located it below the C3Bn–C3Br.1r limit, with an approximate age of 7.5 Ma. In their review of the Neogene mammal zone boundaries in the Iberian Peninsula, Agustí et al. (2001) put this limit back in the place initially proposed by Krijgsman et al. (1996) by taking the MN11 fauna of El Bunker section as a reference and reinterpreting the magnetostratigraphic correlation of Opdyke et al. (1997) (Fig. 5).

van Dam et al. (2001) reinterpreted the correlation between the magnetostratigraphic sections of the lower series of the Teruel Basin, previously established by van Dam (1997) and Garcés et al. (1999), and situated this boundary towards the middle part of the C4n.1n chron; recalibration to CK95 provides an age of 7.432–7.562 Ma (Fig. 9). Although MN11 fauna in El Bunker section could be used to refine this age, this calibration cannot be settled on due to differences in sedimentation rate between the sections. If the calibrated ages provided by these authors for El Bunker de Valcebro 6/7 (MN11; K local zone) and Tortajada B (MN12; L local zone) sites are considered, this boundary should be placed at 7.9–7.5 Ma, spanning from C4n.2n to C4n.1n in CK95 (Table 2).

Afterwards, van Dam et al. (2006) located the MN11/12 boundary at 7.91–7.60 Ma, by calibrating the ages of Tortajada A (MN11) and Masada del Valle 3 (MN12) sites with reference to GPTS04. Similarly, Domingo et al. (2007) proposed an age of 7.834–7.494 (C4n.2n to C4n.1n on the CK95 scale) from the calibrated age of Puente Minero (MN11) and Ademuz (MN12) macromammal sites, which are located in the central and southern sectors of the Teruel Basin, respectively. Gómez Cano et al. (2011) dated this boundary to 8.462–8.072 Ma (C4r.2r to C4r.1r/C4n.2n limit in the CK95 and GK07 scales) in the northern Teruel Basin, considering the calibrated age of the Los Aguanaces (MN11) and Aljezar B (MN12) small mammal sites.

In our 3D stratigraphical model, the age of the MN11/12 boundary has been restricted to 7.93–7.87 Ma (C4n.2n chron), from dating of the Tortajada A (MN11) and Los Aljezares (MN12) sites, respectively. The location of both mammal sites just below and above the guide level 6 enables to calibrate the sites with the GPTS thanks to the El Bunker section.

8.5. The MN 12/13 boundary

Neither the first magnetostratigraphic works in the Teruel Basin, nor those in other basins allowed proposing a dating for the MN12/13 boundary (e.g. Krijgsman, 1996; Opdyke et al., 1997). Based on an undescribed MN13 fauna within sediments attributed to the base of C3An.2n in the Cabriel sections, Opdyke et al. (1997) arbitrarily placed the boundary at the base of this chron. Sen (1997) suggested that this boundary does not match with respect to the age proposed in Turkey and Greece, so that the age should be older than that proposed by Opdyke et al. (1997) and placed even close to the limit C3Br.2r/C3Br.1n.

Agustí et al. (2001) bracketed the MN12/13 boundary between 7.2

and 6.8 Ma (between C3Br and C3Ar chrons) by considering the Cabriel and Fortuna magnetostratigraphic sections (Opdyke et al., 1997; Garcés et al., 1998). After reinterpreting the correlation between Masada Ruea, Masada del Valle, La Gloria, El Bunker and La Roma sections, van Dam et al. (2001) provided the same chronostratigraphic range for this boundary in the Teruel Basin. Nevertheless, the calibration with respect to the CK95 scale proposed by van Dam et al. (2001) moved this boundary to ~6.8 Ma (basal part of C3Ar), because both, Conclud (MN12; local zone L) and Masada del Valle 6 (MN13; local zone M1) sites, have contemporary fauna (Table 2).

Later on, van Dam et al. (2006) dated this boundary to 7.10–7.00 Ma (basal C3Ar) according to the new calibration of the Conclud 3 (MN12) and Masada del Valle 6 (MN13) sites within the GPTS04. Domingo et al. (2007) estimated a wider age range, between 7.011 and 6.319 Ma (C3Bn to C3An.2n chrons), from calibration of sites with macromammal fauna belonging to MN12 (Cerro de la Garita, Los Mansuetos, Conclud Barranco and Valdecebro sites) and MN13 (El Arquillo site) in the northern Teruel Basin with respect to CK95.

In this study, the MN12/13 boundary has been dated to 7.05–6.88 Ma from the calibrated age of Los Mansuetos (MN12) and Masada del Valle 7 (MN13) sites. This age bracket, similar to the proposal of van Dam et al. (2006), is located within the lower part of C3Ar in GPTS scales of Ogg (2012) and Gradstein et al. (2020). Nevertheless, this age could be more closely constrained if Masada del Valle 6 site (MN13), stratigraphically below Masada del Valle 7, would be more precisely located in our stratigraphic framework.

8.6. The MN 13/14 (Turolian/Ruscinian) boundary

This boundary was defined for the first time in the Fuente del Viso (Cabriel Basin), at the base of the Sidufjall subchron (C3n.3n, 4.9 Ma) (Opdyke et al., 1997). This age is younger than its traditional position at the Miocene-Pliocene marine boundary (5.3 Ma). Agustí et al. (2001), after considering the magnetostratigraphic sections of Cabriel and Fortuna (Opdyke et al., 1997; Garcés et al., 1998), interpreted that a minimum age for the MN13/14 boundary should be 4.9 Ma since they believed that the fauna from Fuente del Viso should be considered to belong to MN14 and not to MN13 as indicated by Opdyke et al. (1997). Vangengeim et al. (2005) evidenced clear diachronism after correlating the Mein zones between the Western and Eastern Europe, which forced to extend the duration of the MN14 zone to the lower part of the C3An chron, previously included in MN13 (Fig. 9).

Later, van Dam et al. (2006) placed this boundary in the Teruel Basin in the lower part of C3r, at 5.89–5.79 Ma, from El Arquillo (MN13; local zone M3) and Lomas de Casares 3 (MN14; local zone Ce) sites, considering their calibrated ages with respect to the GPTS04 (Table 2). Likewise, from the age of macromammal sites calibrated to CK95, Domingo et al. (2007) proposed a wider and slightly rejuvenated age range of 5.689–4.825 Ma (C3r to C3n.3n chrons). This attribution is based on the estimated age (5.689 Ma) of several sites with MN13 fauna (Los Milagros, Venta del Moro, Arenas del Rey, and Tariejo de Cerrato) in different basins in Spain (Teruel, Cabriel, Granada and Duero, respectively), as well as the age estimated (4.825 Ma) for the MN14 fauna of the Alcoy Mina site (Alicant North Prebetic Basin).

Based on our model, the MN13/14 boundary in the northern Teruel Basin can be established at 5.15–5.03 Ma on the GPTS scale of Gradstein et al. (2020), so it probably belongs to the Thvera subchron (chron C3n.4n). This age should be taken with caution because the Los Milagros (MN13) and Celadas 8 (MN14) sites used for dating have not been directly correlated with any magnetostratigraphic section, and therefore with the GPTS, so that the age estimation is not as reliable as in other cases (see Supplementary fig. 1).

8.7. The MN 14/15 boundary

The position of this boundary in the Teruel Basin was well

established by Opdyke et al. (1997) between sites with MN14 fauna found in normally magnetized sediments (Orrios 1 and Villalba Alta Río 1) and sites with MN15 fauna in reversely magnetized sediments (Villalba Alta Río 2, 3, 4 and Villalba Alta 5). These authors correlated both magnetozones with C3n.1n (Cochiti subchron) and C2Ar chrons respectively, placing the MN14/15 boundary in their transition, at 4.18 Ma (middle Ruscinian) on the CK95 scale. This assignment is quite consistent with the results of other Spanish basins (Fig. 9) such as Cabriel, Júcar or Guadix-Baza (Sen, 1997; Garcés et al., 1997; Oms et al., 1999; Agustí et al., 2001; Vangengeim et al., 2005).

van Dam et al. (2006) proposed an age for this boundary ranging from 4.32 to 4.15 Ma based on the age, calibrated to the GPTS04 scale, of Villalba Alta Río 1 (MN14; local zone Tr) and Villalba Alta Río 2 (MN15; local zone aM) sites. However, the age assigned to the former site (VAR1; 4.32 Ma) on the GPTS04 scale slightly moves down the MN14/15 boundary to the upper part of chron C3n.1r, which is not realistic because VAR1 is found in sediments with normal polarity. Accordingly, the younger age for this boundary must be <4.30 Ma, that is the age of the lower limit of C3n.1n (Cochiti subchron) on the GPTS04 scale.

Domingo et al. (2007) dated this boundary with macromammals from sites assigned to MN14 (Orrios 1, La Calera and La Gloria 4 sites) and MN15 (Orrios 3 site). They estimated a more recent age for the boundary than previous authors, and placed it at 4.186–4.049 Ma (topmost C3n.1n-lower part of C2Ar on the CK95 scale).

We have estimated an age of 4.20–4.12 Ma (around the C3n.1n to C2Ar chron transition) for the MN14/15 boundary, based on the age of Villalba Alta Río 1 (MN14) and Villalba Alta Río 2 (MN15) sites, calibrated to the Gradstein et al. (2020) scale. The stratigraphic position of the Villalba Alta site (MN15), which practically correlates with Villalba Alta Río 1 (MN14; see Supplementary fig. 8), suggests that the boundary could probably be restricted to the highest part of the Cochiti subchron (4.20–4.19 Ma). This poses the problem that localities very close to each other and in an equivalent stratigraphic position have been assigned to a different mammal zone.

8.8. The MN 15/16 (Ruscinian/Villafranchian) boundary

This boundary was established by Opdyke et al. (1997) in Escorihuela, where sediments containing MN15 fauna (Escorihuela B site), with *Dolomys adroveri*, are ~10 m below two sites with MN 16 fauna (Escorihuela C and A sites), with *Cseria gracilis* and *Mimomys hajnackensis*. Because the existence of a reverse to normal polarity change, just above the MN15 site, the MN15/16 boundary was located near the C2Ar/C2An limit, so corresponding to the Gilbert/Gauss boundary (3.58 Ma). Based on Romanian fauna, Sen (1997) placed this boundary, with some uncertainty, between the C2An.2n chron and the C2An/C2r (Gauss/Matuyama) limit.

Based on the Zújar section (Guadix-Baza Basin) and comparing their results with Opdyke et al. (1997) in the Teruel Basin, Oms et al. (1999) assumed a certain diachrony for this (MN15/16) and the next boundary. They placed the MN15/16 boundary somewhere between chrons C2An.3n and C2An.2n, suggesting that the magnetic reversal registered in the Escorihuela magnetostratigraphic section could correspond to the boundary between chrons C2An.2r and C2An.2n.

Agustí et al. (2001) and, later, van Dam et al. (2006), following the criteria of Garcés et al. (1997) and the reinterpretation of the Escorihuela section by Oms et al. (1999), established the MN15/16 boundary between the chrons C2An.2r and C2An.2n, at 3.2 Ma. From the calibrated ages of sites Escorihuela B and C, respectively, van Dam et al. (2006) established an age range for this boundary between 3.21 and 3.19 Ma. However, Vangengeim et al. (2005), maintained the assignment made by Opdyke et al. (1997).

Domingo et al. (2007) located the boundary between 3.912 Ma, estimated for the Layna site (MN15) in the Tagus Basin, and 3.297 Ma, estimated for MN16 fauna in the El Rincón 1 and Huélago sites in the Júcar and Guadix-Baza basins, respectively.

According to our 3D stratigraphic model, the correlation between the Escorihuela and Villalba Alta magnetostratigraphic sections and the GPTS initially proposed by [Opdyke et al. \(1997\)](#) seems to be more appropriated than that suggested by [Oms et al. \(1999\)](#). The guide level 18 can be followed between both sections, and the relative position of the mammal sites as well as the sedimentary thickness between them has been controlled thanks to other levels represented in the profiles in Alfambra, Orrios and Villalba Alta transects. Therefore, this implies to locate the MN15/16 boundary around the Gauss/Matuyama (C2An/C2r) limit. As below discussed, a detailed correlation reveals that Villalba Alta 5 site (assigned to MN 15) is above Escorihuela C (MN16) (see [Table 1](#)). Moreover, it is showed that both sites are located between 3.61 Ma (Villalba Alta Granja, MN15) and 3.56 Ma (Orrios 5, MN16). Consequently, the age of this boundary can be set between those ages (3.61–3.56 Ma) ([Table 2](#)).

8.9. The MN 16/17 boundary

[Opdyke et al. \(1997\)](#), from faunas in Valdeganga (Júcar Basin), suggested that the MN16/17 boundary is younger than the Olduvai subchron (C2n), < 1.78 Ma. [Garcés et al. \(1997\)](#), considering the *Equus* dispersal event (MN16a/MN16b) found in India and Italy at the top of Gauss, as well as the radiometric ages of the Villafranchian localities in France, restricted the age of the MN16/17 boundary in the Galera section (Guadix-Baza Basin) to the lower Matuyama (subchron C2r.2r), between 2.4 Ma and 2.6 Ma. This age is notably older than that proposed by [Opdyke et al. \(1997\)](#). [Oms et al. \(1999\)](#), after comparing their results from the Zújar magnetostratigraphic section (Guadix-Baza Basin) with those obtained by [Opdyke et al. \(1997\)](#) in Valdeganga, and [Garcés et al. \(1997\)](#) in Galera, assumed that the zone boundary remains poorly constrained and would be better located below the Olduvai subchron ([Fig. 9](#)), probably correlating to the 2.6 Ma glaciation event.

[Agustí et al. \(2001\)](#) placed the MN16/17 boundary close to the C2An/C2r limit, and dated it ca. 2.5 Ma. The interpretation is based on the youngest MN16 locality (Villalba Alta) in the top of chron C2An in the Villalba Alta section of the Teruel Basin ([Opdyke et al., 1997](#)), and the oldest MN17 localities in the sections of Galera ([Garcés et al., 1997](#)) and Zújar ([Oms et al., 1999](#)) in the Guadix-Baza Basin, both correlated with the lower part of the C2r. [Vangengeim et al. \(2005\)](#) aged this limit to the uppermost part of C2An (subchron C2An.1n).

In the northern sector of the Teruel Basin, the boundary between zones MN16 and MN17 (early-late Villafranchian boundary) is not yet well defined. The youngest MN16b locality (Concud Estación 2) is found in C2r (~10 m stratigraphically above the limit with C2An.1n) in the Concud section ([Opdyke et al., 1997](#)). The only MN17 locality (Rotonda Teruel-Centro) has been correlated with the subchron C2r.1r and is located ~8 m below the limit with C2n in the Masada Cociero section ([Ezquerro et al., 2016; Ezquerro, 2017](#)). The stratigraphic correlation of these two magnetostratigraphic sections has allowed calibrating the age of both localities and proposing an age of 2.54 and 1.95 Ma, respectively (see Supplementary fig. 2). The MN16/17 boundary in the Teruel Basin is established somewhere within this age range ([Table 2](#)).

9. Discussion

9.1. The bio-chronostratigraphic model of the Teruel Basin

The new bio-chronostratigraphic model proposed for the northern sector of the Teruel Basin ([Fig. 8](#)), based on a robust 3D stratigraphic architecture, has provided numerical ages for 72 mammal sites ([Table 1](#)). It should be remembered that the estimated age error usually ranges from 10 to 20 ka, depending on the category of the fossil site, which is related to the reliability of the correlation between fossil sites and magnetostratigraphic sections. Numerical ages are compiled in Supplementary Table 1, together with others estimated by [van Dam et al. \(2001, 2006, 2020\)](#), [Domingo et al. \(2007\)](#) and [Gómez Cano et al.](#)

(2011) for the same fossil sites, and other 54 fossil sites in the northern sector of the Teruel Basin. Moreover, the age data are represented in [Fig. 10](#), which shows a complete, continuous and extraordinary record of mammal sites, from 9 Ma to 2 Ma in the Teruel Basin. The comparison of our results in this basin with previous calibrations of fossil sites and MN zones shows general agreement, although some differences are brought to light ([Fig. 10](#) and Supplementary Table 1).

Recent studies by [Domingo et al. \(2007\)](#) and [Gómez Cano et al. \(2011\)](#) are based on a smaller number of fossil sites from this basin, and commonly show largest discrepancies in their age. In both papers, some fossil sites are given the same absolute age even though they are not in the same stratigraphic level. The age assigned to each site in these works corresponds to the mean value of the upper and lower limit of the chron or subchron which the site belongs to. This procedure for age assignment normally increases uncertainty for two reasons. First, the relative position of the site within the chron is not taken into consideration, even being close to a chron limit. Second, the longer the time spanned by the chron, the higher the age uncertainty is. In some cases, this procedure leads to propose apparently precise but spurious ages for certain MN boundaries, especially when two paleontological sites of different zones are in the same chron. As an example, [Gómez Cano et al. \(2011\)](#), using the MLAEO method ([Alroy, 2000](#)), date to 9.130 Ma both Peralejos C (MN10) and Peralejos D (MN 11) sites, which prompted them to assign this age to the MN10/MN11 boundary, although Peralejos C is 5 m below Peralejos D, and PERD belongs to MN10 zone (see Supplementary fig. 5). The same case occurs for the MN9/MN10 boundary, dated to 10.133 Ma by [Gómez Cano et al. \(2011\)](#) ([Table 2](#)).

In other cases, the numerical ages of fossil sites estimated from the MLAEO method are inconsistent with those inferred from magnetostratigraphy. Based on this method, [Domingo et al. \(2007\)](#) proposed an age of 9.850 and 8.789 Ma for sites Masía del Barbo 2A (MB2A) and Masía del Barbo 2B (MB2B), respectively. In the GPTS by [Cande and Kent \(1995\)](#), as also in the more recent one of [Gradstein et al. \(2020\)](#) and other GPTS (Supplementary Table 2), these ages correspond to the C5n and C4An normal chrons, respectively. However, the MB2A and MB2B sites had previously been robustly correlated with the chrons C4Ar.2r and C4Ar.1n, respectively, of the Masada Ruea magnetostratigraphic section ([Garcés et al., 1999; van Dam et al., 2001, 2006](#)). In our opinion, the uncertainties and artifacts mentioned above, point that this method of assigning ages, and consequently the estimated ages themselves, should be considered with caution. Besides, it is not acceptable to uncritically use ages of mammal sites from different sedimentary basins, sometimes located at a great distance from each other (e.g., disregarding the effect of migration time of fauna between those regions).

Our age calibration for fossil sites is more similar, both in number of sites and age estimation, to those proposed by [van Dam et al. \(2001, 2006\)](#) ([Fig. 10](#) and Supplementary Table 1). The age of the 37 fossil sites shared by our study and that of [van Dam et al. \(2006\)](#) shows a very good correlation ([Fig. 11](#)), with the slope of the regression line (1.024) very close to 1, and a relatively low data dispersion (correlation coefficient $R^2 = 0.98$), indicating comparable age estimations between both approaches. Detailed comparison reveals that correspondence with respect of [van Dam et al. \(2006\)](#) is quite high in some intervals (e.g., from 8 to 6 Ma and 4.4 to 3.8 Ma). However, in other cases our model results in rejuvenating ages (9.6 to 8.7 Ma and 5 to 4.4 Ma intervals) or ageing them (3.8 to 3 Ma interval) ([Figs. 10 and 11](#)). Finally, some isolated fossil sites (e.g., ALF, BUN and BUN 4/5) have significant age differences.

Regarding the 9.6 to 8.7 Ma interval, the rejuvenated ages we propose (~0.3 Ma) for the mammal sites fit well those previously estimated by [van Dam et al. \(2001\)](#) (see [Fig. 10](#)). The new ages provided later by [van Dam et al. \(2006\)](#) were not justified or discussed. Nor the magnetostratigraphy reinterpretation or the age calibration to the 2004 time-scale seem to justify the new proposal. In the period between 5 and 4.4 Ma, we propose the rejuvenation by ~0.5–0.8 Ma of Lomas de Casares (LC3, LC2 and LC1 in stratigraphic order) and Celadas (CE8, CE5, and

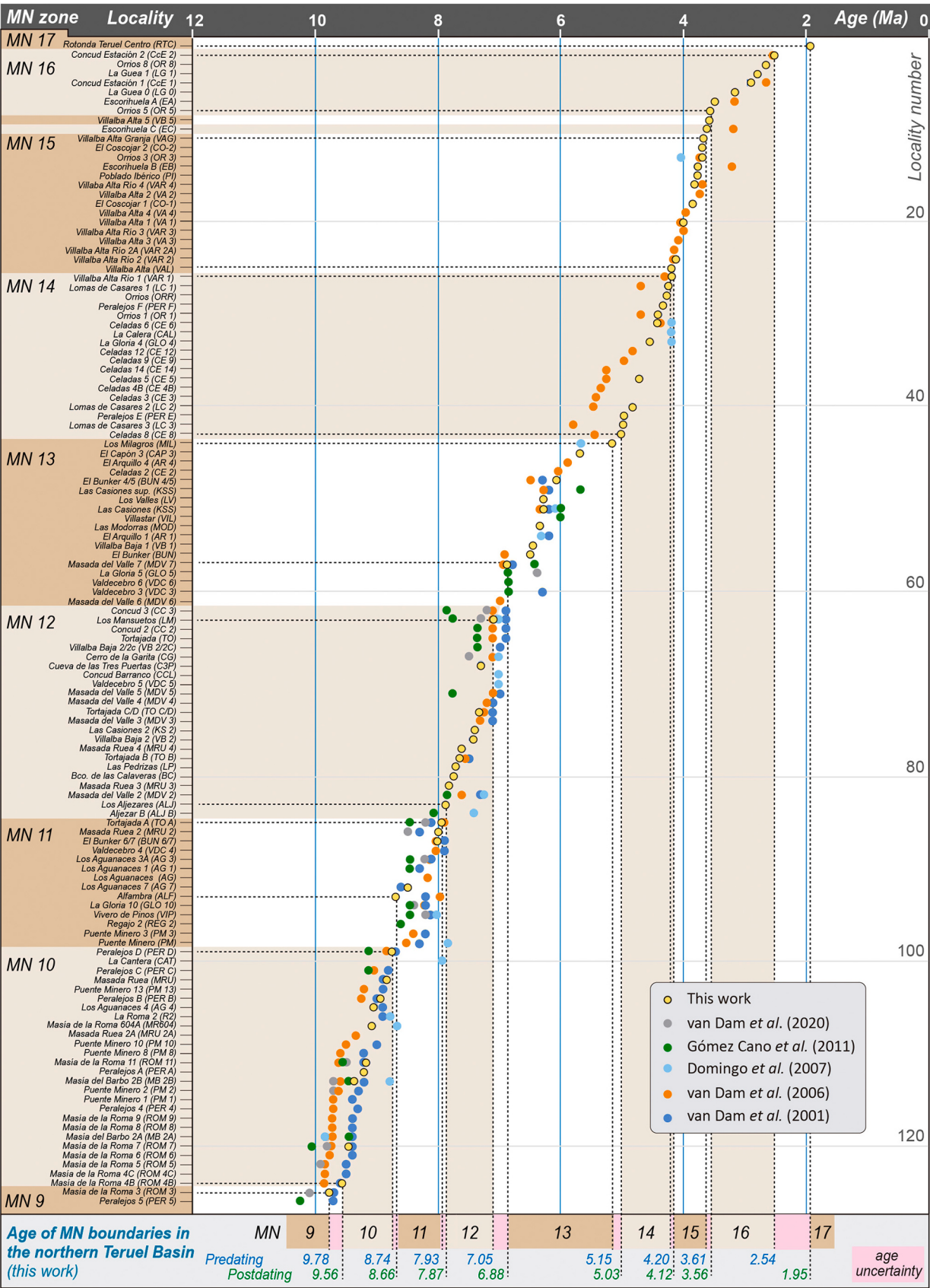


Fig. 10. Comparison between the ages estimated by different authors for the mammal sites of the Teruel Basin and those established in this work, and proposed age ranges for the MN boundaries. Locality number indicates the position of each site in the Supplementary Table 1. Ordering follows the proposal by van Dam et al. (2001, 2006) except for the sites relocated in this work.

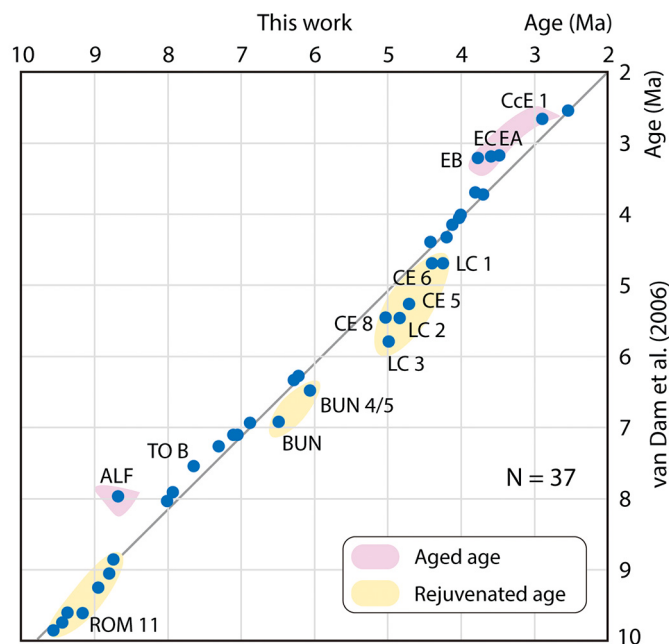


Fig. 11. Comparative cross-plot of the ages of mammal sites between this work and the previous results by van Dam et al. (2006).

CE6) sites, mainly based on the relative position of these sites with respect to the correlation level 9 (see Supplementary fig. 4). As we have previously discussed, this significant correlation level has been dated to 4.9–5.0 Ma (Supplementary notes 2) after reinterpreting the upper part of the El Bunker magnetostratigraphic section (compare Figs. 5 and 6). In any case, it should be pointed out that this interval is the poorest constrained by magnetostratigraphy in the whole sedimentary succession. Rejuvenating El Bunker sites (BUN and BUN 4/5) also responds to this new reinterpretation.

Regarding the period for which we propose older ages (from ~3.8 to 3 Ma), the proposal for Escorihuela (EA, EB, and EC) and Concud Estacion 1 (CcE1) mammal sites is based on the Escorihuela and Masada Cociero magnetostratigraphic sections (see Figs. 5 and 6). As indicated in section 6.2, our 3D stratigraphic model for this region supports the interpretation by Opdyke et al. (1997) for the Escorihuela profile, instead of that of van Dam et al. (2006) that resulted in the ageing of the Escorihuela fossil sites. Moreover, ageing of CcE1 arises from detailed correlation of the Concud and Masada Cociero magnetostratigraphic sections and conversion to the 2020 timescale (Gradstein et al., 2020). Furthermore, the Alfambra site (ALF) has been also aged based on its robust stratigraphic correlation with the Masada del Valle magnetostratigraphic section and its assignment to the chron C4r (Supplementary fig. 2).

9.2. Towards the standardization of European Neogene Mammal zones: the MN zones and continental stages boundaries

From the early days, Neogene mammal paleontologists have disagreed about the definition and significance of the continental mammal units and their use as chronological scale (e.g. Dam, 2003; Hilgen et al., 2012). Two approaches have traditionally existed in the interpretation of the classical MN system (unspecific in Mein's definition; Mein, 1975): biostratigraphic and biochronologic. The first one presents the biozonation and chronozonation on a stratigraphic sense, on the basis of rock units with defined boundaries, therefore their stratotypes can be established (e.g. Steininger, 1999; Agustí et al., 2001). From the biostratigraphic interpretation emerge the “stages” (chronostratigraphic units) and their respective “ages” (geochronologic divisions). The biochronologic approach examines only the faunal content of the localities,

which must be composed of complete associations of mammals with a well-constrained time calibration (e.g. Bruijn et al., 1992; Lindsay, 2003). The temporal order of the reference localities supports the biochronological time scale, but there are no boundaries.

Both approaches can be undermined by problems such as those related to long-distance correlations, lack of fauna records in stratigraphic successions, quantity and quality of faunal assemblages, and the appearance of new taxa, among others. These problems are unavoidable in any chronological system, but vertebrate paleontologists have adopted these approaches for many years to define the boundaries of biochronological units (Lindsay et al., 1990; Lindsay, 2003). The rapid and irreversible morphological evolution of continental mammal faunas makes them more useful stratigraphic markers than most marine faunas (van Dam et al., 2006; Hilgen et al., 2012), but requires more robust temporal information in order to obtain significant results. It gives rise to very complex chronological systems or nomenclatures (e.g. van Dam et al., 2001; Dam, 2003), which add difficulty to the communication between researchers. If we want the reference MN system to be useful for non-paleontologists who need to temporarily constrain key events, such as stratigraphic, tectonic or paleoclimatological, the mammal-based chronology should be user-friendly and, as far as possible, specific for each region. This is especially important since many of these events (e.g. tectonism, rapid climatic changes) may be the primary responsible for discontinuities in distribution and evolution of mammals, resulting in biogeographic provinciality and endemism (Lindsay et al., 1990).

Although successive studies continue refining the temporal calibration of mammal zones and continental stages (e.g. Agustí et al., 2001), uncertainties in the calibration of some MN boundaries or transitions still exist. These uncertainties are sometimes associated with transitions between fauna assemblages, which are more inhomogeneous in time and space, but they can also be related to the low resolution of magnetostratigraphic sections and the discontinuous record of mammals. The first is especially true when larger regions are considered in the analysis. This has led a number of researchers to question the usefulness and isochrony of the MN boundaries (e.g. Bruijn, 2001; van Dam et al., 2001). Although uncertainties have been reduced, it is true that some of our limits are still quite wide in time (e.g. the MN9/MN10, MN12/MN13 and MN16/MN17 boundaries, Fig. 10) despite our study has focused on even with a single basin. Even considering our study has focused on a single basin exceptionally rich in mammal sites and magnetostratigraphic studies, the discontinuity of the fossil record gives rise to apparent diachrony of MN boundaries. Further studies with a strong stratigraphic frame, similarly to the here presented, will help to reduce such uncertainty range in each basin and therefore to enable more accurate correlation between basins and provinces.

On the other hand, as discussed below, the recent multivariate interpolation methods have become a powerful tool to reach optimal calibration of mammal localities (e.g. Alroy, 1998; van Dam et al., 2006; Domingo et al., 2007). Nevertheless, these methods have limitations for temporal scaling of mammal sites and building robust chronological systems (e.g. Dam, 2003). At this moment, the faunal assemblages and calibration of most MN units and their boundaries in the Teruel Basin are already well-defined and they are reasonably isochronous for allowing accurate regional correlation on a basin scale. Our integrated 3D chronostratigraphic model should be used to refine the interpolation methods, adding more temporal precision to the calibration and interpolation between localities, which could improve the chronological system in the future.

In any case, all efforts made to specify, as far as possible, the MN zones by means of calibration methods will result in better dating of key stratigraphic successions, such as the northern Teruel Basin. Taking into account the good correlation that exists between the MN zones in the distinct western European provinces, especially in the Iberian Peninsula, several authors have recently suggested that a possible solution could arise from focusing on accurate correlations of the European reference localities with the Spanish scale of small mammals (Bruijn, 2001; Dam,

2003).

The new bio-chronostratigraphic model of the Teruel Basin has made it also possible to re-evaluate the MN boundaries established in previous works (see Fig. 8). This study proposes a more accurate calibration for some boundaries with data coming exclusively from this basin (Fig. 9). We would like to emphasize that all boundaries present a certain diachronism or age uncertainty, which is realistic given the geologic record and the conceptual idea of MN boundary.

The temporal range of boundaries of the mammal zones is defined between the position of the last locality of a given MN zone and the first of the next one. The time ranges are normally around 0.1 Ma, but some boundaries, such as MN9/MN10, MN12/MN13 and MN16/MN17, still remain wider (from ~0.2 to ~0.6 Ma). In the MN9/MN10 boundary, this resulted from poor correlation between fossil sites and magnetostratigraphic sections. In the MN12/MN13 boundary, a hiatus prevented better calibration and there were too few mammal sites of categories 1 and 2. In the MN16/MN17 boundary, sites were too far apart in time.

In addition, the diachronic character of the MN15/MN16 boundary results from the surprising stratigraphic and magnetostratigraphic relationship between the Villalba Alta and Escorihuela sites, already mentioned by Ezquerro (2017). The stratigraphic location of the Escorihuela sites shows slight differences between the works of Mein et al. (1990) and Opdyke et al. (1997). The correlation proposed by Ezquerro (2017) focused on the strong stratigraphic similarities with respect to the first work and the sites were located on the basis of the stratigraphic position, being Escorihuela C located at the top of C2Ar. After considering the interpretation by Ezquerro (2017), we have enhanced the stratigraphic position of the Escorihuela B and C sites with respect to the magnetostratigraphy of Opdyke et al. (1997), resulting in the location of Escorihuela C (MN16) just above the limit C2Ar-C2An.3n. The site VA5 (MN15), maintains its ascription to the C2An.3n chron in a higher position (Fig. 7). Since the chron limit is by definition isochronous, the three possibilities are that: i) a guide fossil remains undiscovered in VA5, ii) both fauna associations coexisted in some way during a time interval (unlikely at intrabasinal scale), iii) and the correlation between Escorihuela and Villalba Alta could need revision.

Our approach, the integration of biostratigraphic and magnetostratigraphic data into a robust 3D stratigraphic framework of the basin, could be used to pinpoint uncertainties and contribute to a better correlation between basins and provinces. In addition to building a more robust chronostratigraphic scenario, it facilitates the interpretation of environmental changes, tectonosedimentary relationships, and the evolution and migration of continental fauna in the basin. Further improvement of the model and in the calibration of the age of mammal sites could come from refining ages thanks to sedimentary cyclicity studies which can allow to bring to light changes in the sedimentation rate over time, avoiding to assume constant sedimentation rates.

Moreover, this new, consistent chronostratigraphic framework should facilitate the achievement of what is, in our view, a pending task: the re-definition of a stratotype for the Turolian continental stage. The original definition (Crusafont, 1965) in Los Mansuetos area, which enjoyed a large consensus in the scientific community at that time, was based on the high diversity of mammal fauna in the Teruel Basin. Nevertheless, it is widely acknowledged that the chosen section is not entirely satisfactory since: (i) the number of mammal sites, especially MN12 sites, are insufficient to define the precise limits of the Turolian (Calvo et al., 1999); (ii) the structural complexity of the northern and western slopes of Los Mansuetos mesa, deeply affected by extensional faults and karst subsidence deformation (Gutiérrez et al., 2012; Ezquerro, 2017) has made difficult for decades to reconstruct the relative position of the fossiliferous levels. Los Mansuetos presents a continuous stratigraphic succession with several fossil sites assigned to MN11 to MN13, including the reference localities for, at least, six micromammal species (Calvo et al., 1999). Nevertheless, in the eastern slope only sites belonging to MN11 and MN13 zones have been recognized in the same section, being most of the MN12 sites located in the

western, complex area, and the youngest MN13 ones disseminated throughout the hill. This situation difficulties a highly reliable vertical arrangement of the Los Mansuetos sites.

In our view, the Cerro de los Aldabades area (San Blas transect Fig. 3 and Sup. Fig. 2) could be more adequate for a new definition of the Turolian stratotype. It hosts all the Alfambra, Masada del Valle and Masada Ruea mammal sites (>10 sites), covering the entire MN11 to MN13 zones. Besides, several closely located sites, as El Regajo and Puente Minero, contain faunal assemblages within the same range (> 9 sites), which could reinforce the definition. The stratigraphic arrangement is well expressed in nearly horizontal beds not affected by faults, which facilitates correlation between fossil sites and the establishment of the base and the top of any MN zone, and therefore of the stratotype.

10. Conclusions

The stratigraphic study, which includes logging of 72 sections and precise correlation using up to 20 sedimentary guide levels, has led to characterize in detail the stratigraphic architecture of the Neogene sediments in the northern sector of the Teruel Basin. The 3D stratigraphic model has been the basis for the establishment of a new bio-chronostratigraphic model for the sedimentary record of the basin, which span from >10 Ma to 2 Ma. This model has been based on the review and incorporation of (i) the 72 most representative of the >150 mammal localities, and (ii) the 11 magnetostratigraphic sections existing in this sector of the basin, all of them located stratigraphically or correlated with the new stratigraphic profiles. Calibration of the bio-chronostratigraphic model to the 2020 GPTS has made it possible to provide an estimate of the numerical age for the correlation guide levels and the fossil sites.

A review and discussion of the current ages of the boundaries of Neogene mammal zones in the Teruel Basin have allowed proposing some changes for boundaries MN 9/10 to MN 16/17, which have been bracketed as follows:

- (i) MN9-MN10: between 9.78 Ma (Masía de la Roma 3; base of C4Ar.3r chron) and 9.56 Ma (Masía de la Roma 4; middle part of C4Ar.2r chron).
- (ii) MN10-MN11: between 8.74 Ma (Peralejos D) and 8.66 Ma (Alfambra), at the lower part of C4r.2r chron.
- (iii) MN11-MN12: between 7.93 Ma (Tortajada A) and 7.87 Ma (Los Aljezares), at C4An.2n chron.
- (iv) MN12-MN13: between 7.05 Ma (Los Mansuetos) and 6.88 Ma (Masada del Valle 7), within the lower part of C3Ar.
- (v) MN13-MN14: between 5.15 Ma (Los Milagros) and 5.03 Ma (Celadas 8), probably belonging to the Thvera subchron (chron C3n.4n).
- (vi) MN14-MN15: between 4.20 Ma (Villalba Alta Río 1) and 4.19 Ma (Villalba Alta), at the highest part of the Cochiti subchron (C3n.1n).
- (vii) MN15-MN16: between 3.61 Ma (Villalba Alta Granja) and 3.48 Ma (Orrios 5), around the Gauss/Matuyama (C2An/C2r) limit.
- (viii) MN16-MN17: between 2.54 Ma (Concud Estación 2; C2r chron) and 1.95 Ma (Rotonda Teruel-Centro; subchron C2r.1r).

The calibration of the MN boundaries in the basin has increased considerably, being generally established with an uncertainty range of ± 0.2 Ma, except for the boundary MN 16/17 (± 0.6 Ma) due to the limited number of mammal sites.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.earscirev.2022.104223>.

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