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Hipparion dispersal in Europe: magnetostratigraphic constraints from the Daroca area (Spain).

La migración de Hipparion *en Europa: datos magnetoestratigráficos de la zona de Daroca (España).*

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Abstract: The Nombrevilla section in the Calatayud-Daroca basin (Central Spain) bears one of the best late Aragonian to early Vallesian large and small vertebrate fossil records in Europe, including important findings of the equid *Hipparion*. Magnetostratigraphic dating of the Nombrevilla section thus provides further age constraints on the timing of *Hipparion* dispersal in Europe, a bioevent which defines the base of the Vallesian mammal stage. Correlation of the Nombrevilla magnetic polarity stratigraphy to the geomagnetic polarity time scale is supported by the identification of the characteristic long normal chron C5n in the upper half of the section, in association with early Vallesian (early late Miocene) fossils. The classic mammal fossil site Nombrevilla 1, recording the earliest occurrence of *Hipparion*, correlates to the lower third of chron C5n, and yields an interpolated age of about 10.7-10.8 Ma. This age is in agreement with magnetostratigraphic dating of earliest occurrences in Siwaliks of Pakistan and some 40Ar/39Ar ages of Mediterranean sites. The youngest pre-*Hipparion* large mammal fossil record corresponds to Nombrevilla 9, a site wich approximately correlates to chron C5r.1n, at about 11.1 Ma. This result is nearly in conflict with the data from the Vallès-Penedès, where a *Hipparion* bearing site is correlated to the same chron. In addition, Nombrevilla 9 yields a small mammal assemblage which corresponds to local zone H, a biozone wich was classically correlated to the lower Vallesian. This implies a diachrony of about 300 kyr between the lower boundary of zone H and the first occurrence of *Hipparion* (base of the Vallesian) in the Calatayud-Daroca basin. Correlation of the Aragonian levels of Nombrevilla 2, 3 and 4 is not yet certain and would require further downward extension of the magnetostratigraphy in a neighbouring section. Nevertheless, we can confidently say these localities are younger than 11.6 Ma.
Key words: *Hipparion*, Biostratigraphy, Magnetostratigraphy, Vallesian, Late Miocene, Calatayud-Daroca Basin, Spain

Resumen: La sucesión estratigráfica de Nombrevilla en la cuenca de Calatayud-Daroca (Cordillera Ibérica) contiene uno de los más ricos registros de macro y microvertebrados fósiles del tránsito Aragoniense/Vallesiense. El estudio magnetoestratigráfico de Nombrevilla aporta nuevos datos sobre la cronología de la aparición de *Hipparion*, un bioevento que define la base del piso Vallesiense. La correlación con la escala de tiempo de polaridad geomagnética está basada en la identificación de C5n, un cron de más de 1 Myr de polaridad normal que es característico del Mioceno superior. La localidad clásica Nombrevilla 1, que representa el registro más antiguo de *Hipparion*, se correlaciona con el tercio inferior del cron C5n, y le corresponde una edad interpolada de 10.7-10.8 Ma. Este dato se corresponde muy bien con la datación magnetoestratigráfica del mismo bioevento en Siwaliks (Pakistán) así como las dataciones radiométricas 40Ar/39Ar en otras localidades de la región mediterránea. La localidad con macrovertebrados más alta sin *Hipparion* en la serie de Nombrevilla es Nombrevilla 9, que se correlaciona aproximadamente con el cron C5r.1n (11.1 Ma). Este resultado no se corresponde exactamente con los resultados del Vallès-Penedès, donde una edad muy similar se obtiene para la primera aparición de *Hipparion*. Aparte, Nombrevilla 9 es particularmente significativa puesto que muestra una asociación de microvertebrados correspondiente a la zona local H, que clásicamente se había identificado con el Vallesiense inferior. Los nuevos datos señalan una diacronía de cerca de 300 kyr. entre el limite inferior de la zona H y la aparición de *Hipparion* en Calatayud-Daroca. La correlación de las localidades del Aragoniense superior Nombrevilla 2, 3 y4 es relativamente incierta, si bien es seguro que se encuentran en la parte superior del cron C5r, con una edad no menor que 11.6 Ma.
Palabras clave: *Hipparion*, Bioestratigrafía, Magnetoestratigrafía, Vallesiense, Mioceno Superior, Cuenca de Calatayud-Daroca, España

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INTRODUCTION

The appearance of *Hipparion* defines the base of the Vallesian stage (CRUSAFONT, 1948) and is one of the key bioevents in the continental Neogene chronology of the Mediterranean region. It is believed that an American ancestor of this grazing, three-toed equid crossed the Bering strait at the time of a sea level lowering at or near the middle-late Miocene transition (WOODBURNE *et al.,* 1981; OPDYKE, 1990) and underwent rapid dispersal over Eurasia and Africa. It is presumed that *Hipparion* met no competition in the Old World from formerly immigrated browsing equids such as *Anchitherium*, which were distinctly adapted to forest-like biotopes (BERNOR *et al.,* 1980).

A long lasting debate concerning the timing of *Hipparion* dispersal in Eurasia started early in the 70's when it was considered as an isochronous event taking place in the late Serravallian at about 12.5 Ma (BERGGREN AND VAN COUVERING, 1974). Further magnetostratigraphic studies provided strong evidences for a younger early Tortonian age of the *Hipparion datum* in the Siwaliks of Pakistan (BARRY *et al.*, 1982). Same results were obtained in the Miocene Sinap Formation of Central Anatolia (KAPPELMAN *et al.,* 1996). Also, radiometric dating of key sites in Europe suggested early Tortonian ages between 11.5 +/- 0.5 Ma (BERNOR *et al.,* 1988) and 10.3 Ma (STEININGER *et al.,* 1996). To date, no paleomagnetic data has been reported from the central and eastern Europe *Hipparion* sites, probably because of unsuitable outcrops for magnetostratigraphy.

Some attempts to date the arrival of *Hipparion* to the Iberian peninsula were carried out in the last decade. In the Duero Basin, the earliest occurrence of *Hipparion* in the Torremormojón section was correlated to the middle part of chron C5n (KRIJGSMAN *et al.,* 1996). In this section, *Hipparion* was found in association with *Cricetulodon*, a cricetid which appears in the late early Vallesian (DAAMS *et al.,* 1988; AGUSTÍ & MOYÀ-SOLÀ 1991; DAAMS *et al.,* 1998; DAAMS *et al.,* 1999). Therefore it was of little use for constraining the earliest occurrence of *Hipparion* in the Iberian peninsula. Magnetostratigraphic studies of Vallesian sites in the Vallès-Penedès Basin suggested an age of 11.1 Ma for the earliest *Hipparion* findings in the Montagut composite section (GARCÉS *et al.,* 1997). Unfortunately, pre-*Hipparion* large mammal sites could not be found in the studied magnetostratigraphic sections of the Vallès-Penedès, and the datum remained loosely bracketed.

In order to better bracket the timing of Hipparion dispersal it is necessary to find a continuous record of the Aragonian to Vallesian transition in a rich fossiliferous single stratigraphic section. The Nombrevilla section is one of the few satisfying these prerequisites, and shows, in addition a very good accessibility and high outcrop quality. Magnetostratigraphic dating of the Nombrevilla section was regarded of top interest by researchers of the Universidad Complutense (Madrid) and the Museo Nacional de Ciencias Naturales (CSIC, Madrid). In this paper we will present the results of a joint project which was particularly impulsed by Remmert Daams in 1997, and thanks to which we could share with Remmert some wonderful field campaigns in Daroca.

THE NOMBREVILLA SECTION

The Villafeliche-Daroca area, in the Calatayud-Daroca Basin (Central Spain), is best known among paleontologists for its very rich and complete record of the early to middle Miocene continental faunal record, which led to the definition of the Ramblian (DAAMS *et al.,* 1988) and Aragonian (DAAMS *et al.,* 1977) continental stages. Further magnetostratigraphic studies led to the development of a robust chronological frame for this area (KRIJGSMAN *et al.,* 1994; KRIJGSMAN *et al.,* 1996; DAAMS *et al.,* 1999).

To the east, the Daroca-Nombrevilla area (Fig. 1), does also have a very rich fossiliferous record of the middle to late Miocene (Aragonian/Vallesian) transition. The lithostratigraphic frame consist of about 200 meters of alluvial red beds alternating with shallow lake marls and limestones. The lower part of the sedimentary sequence is dominated by red clayish alluvial units. The oldest mammal site is found in the Toril section, and provides an upper Aragonian age (G3 local zone). The Toril mammal locality is equivalent to Las Planas 5H, at the top of the Aragonian type section in Villafeliche (DAAMS *et al.,* 1999; ALCALÁ *et al.,* 2000). The upper part of the sequence is best represented in the Nombrevilla section (Fig. 2), which mainly consists of alluvial red clays alternating with shallow lacustrine limestones and, locally interfingering gravel and sandstone lenses. Three late Aragonian mammal sites are clustered in the red clayed interval at the base of the Nombrevilla

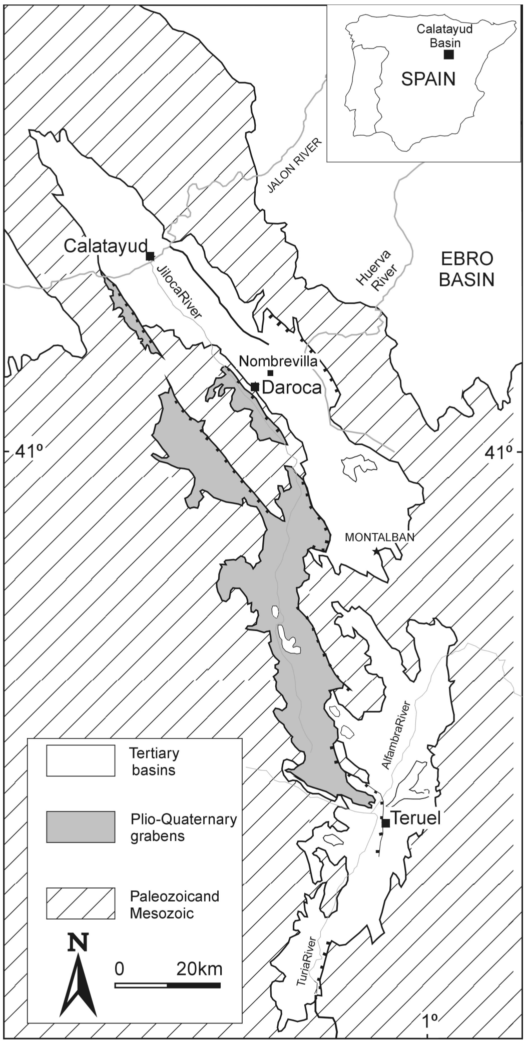

Figure 1. Location map of the Nombrevilla section in the context of the Calatayud-Daroca Basin (Spain).
Figura 1. Situación de la sucesión estratigráfica de Nombrevilla en el marco de la Cuenca de Calatayud-Daroca.

section. Among these, Nombrevilla 2 yielded a rich large mammal assemblage where *Hipparion* was absent. About 35 meters above Nombrevilla 2 there is a new locality, Nombrevilla 9 (ALCALÁ *et al.,* 2000), that yielded a rich small and large mammal assemblage. The rodents are typical of zone H (*Hispanomys, Megacricetodon ibericus*), while *Hipparion* is not yet present among the large mammals (PELÁEZ-CAMPOMANES *et al.,* 2000) (ÁLVAREZ-SIERRA et al, this volume). First occurrence of *Hipparion* is reported 15 meters higher in the section at the classic site of Nombrevilla 1, within a calcareous interval in the middle part of the section. Among small mammals, four more sites, Nombrevilla 10, 13, 14 and 19 yielded a sequence of early Vallesian faunal assemblages (ALCALÁ *et al.,* 2000).

MAGNETOSTRATIGRAPHY

The 120 meters thick Nombrevilla section was sampled for magnetostratigraphy at intervals of 0.5 to 3 meters (80 sites, average 1.5 m/site), depending on suitability of rocks and outcrop. Two or three cores per site were drilled with a portable drill and oriented in the field by means of a magnetic compass and clinometer.

Analysis of the samples in the paleomagnetic laboratory consisted in progressive thermal demagnetisation, at 30C to 50C steps, of one or two samples per site. Demagnetisation diagrams reveal a two-component natural remanent magnetisation. A low temperature component yields a direction parallel to the present field and is attributed to viscous magnetisation. A high temperature characteristic component presents both normal and reversed polarities. The direction of the characteristic paleomagnetic component was successfully isolated from a recent geomagnetic field viscous component after heating to 200C-250C. Complete demagnetisation required temperature steps up to 600ºC. Red mudstones carried a high intensity remanent magnetisation and yielded the most reliable paleomagnetic directions in all cases. In the upper half of the section, where lacustrine calcareous sediments where more frequent, paleomagnetic results where of lesser quality. Samples from the whitish calcareous and marly intervals did not always provide stable paleomagnetic components.

Paleomagnetic directions for each sample were obtained by visual inspection of the demagnetisation plots (Fig. 3). Paleomagnetic declination and inclination was computed by means of least squeare analysis, and then latitude of the Virtual Geomagnetic Pole (VGP) was calculated. Positive and negative VGP latitudes were interpreted as normal and reverse polarities respectively (Fig. 2). A sequence of 7 magnetozones (4 reverse and 3 normal) was determined, each magnetozone being defined on the basis of the occurrence of two or more successive magnetostratigraphic sites of same polarity. Single site magnetozones where considered less reliable and where not taken

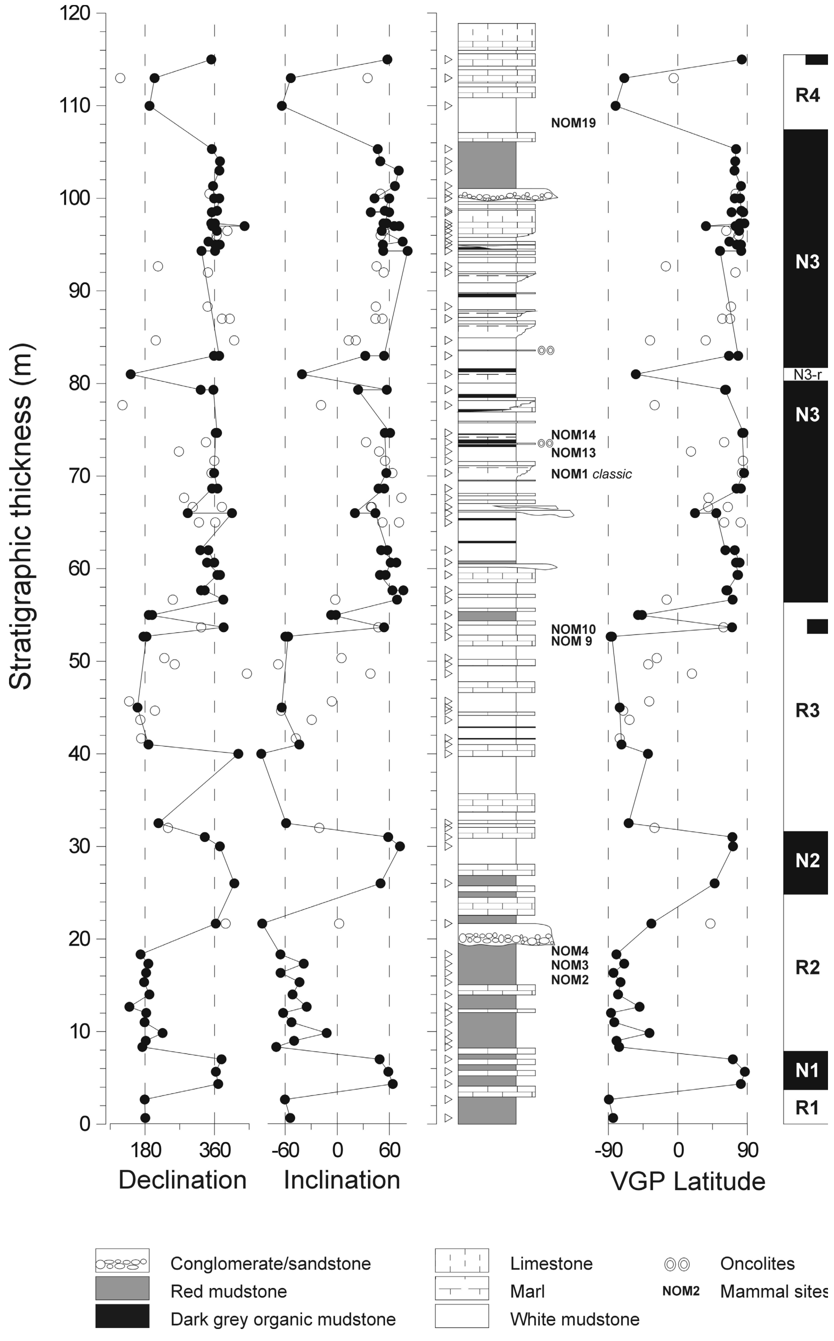

Figure 2. Magnetostratigraphy of the Nombrevilla section. Plots to the left of the lithology log represent declination and inclination of the characteristic paleomagnetic direction of individual samples. Black (open) dots represent reliable (unreliable directions). Negative latitude of the Virtual geomagnetic Pole (right plot) indicates reversed (R1 to R4) polarity in the magnetostratigraphy log. Positive latitudes indicate normal (N1 to N3) polarity.

Figura 2. Magnetoestratigrafía de la sucesión de Nombrevilla. A la izquierda, declinación e inclinación de la dirección paleomagnética característica de cada muestra. Círculos negros y blancos representan direcciones de alta y baja calidad respectivamente. Latitudes positivas y negativas del Polo Geomagnético Virtual (derecha) indican polaridades normales (N1 a N3) e inversas (R1 a R4) respectivamente.

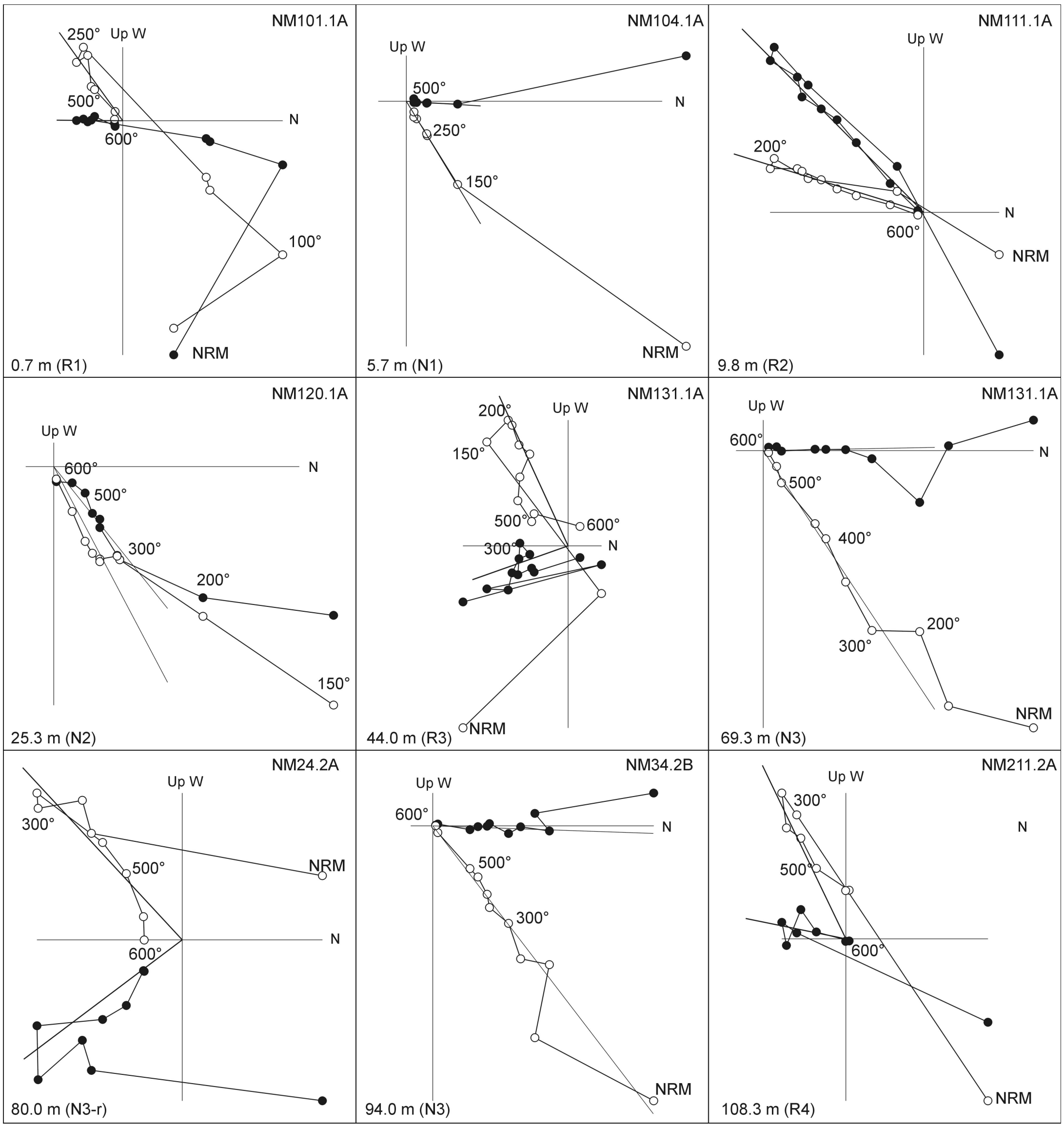

Figure 3. Some stepwise thermal demagnetisation diagrams of representative samples from each of the defined magnetozones in the Nombrevilla section. Stratigraphic position in meters indicated in the lower left corner of each Zijderveld diagram.
Figura 3. Diagramas de desmagnetización térmica progresiva de muestras representativas de cada magnetozona de la sucesión de Nombrevilla. La posición estratigráfica de cada muestra está indicada en el margen inferior izquierdo..

into account for the correlation to the time scale as discussed below.

CORRELATION TO THE TIME SCALE

A feasible correlation of the Nombrevilla section to the geomagnetic polarity time scale is proposed on the basis of its characteristic pattern of magnetozones and the biostratigraphic constraints of the abundant fossil localities of late Aragonian to early Vallesian age (Alcalá *et al.,* 2000). The co-occurrence of the long normal magnetozone N3 in the upper half of the section (fig. 4) with early Vallesian fossils provides unambiguous correlation to chron C5n.2n. This is in

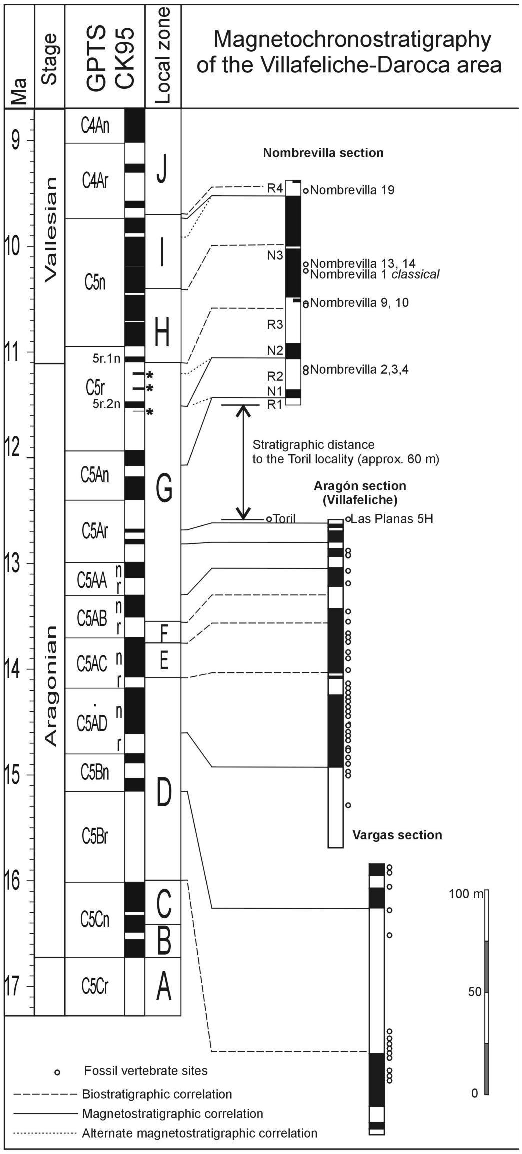

Figure 4. Correlation of the Nombrevilla section to the time scale in the frame of the bio and magnetochronology of the Villafeliche-Daroca area. Magnetostratigraphy of the Aragon and Vargas sections in the Villafeliche area taken from KRIJGSMAN et al., (1994), KRIJGSMAN et al., (1996) and DAAMS et al., (1999). Asterisks in the CK95 time scale indicate the position of some potential new subchrons within C5r (ABDUL AZÍZ 2001).

Figura 4. Correlación de la sucesión magnetoestratigráfica de Nombrevilla con la escala de tiempo de polaridad geomagnética en el marco de los datos magnetocronológicos del área de Villafeliche de KRIJGSMAN et al., (1994), KRIJGSMAN et al., (1996) y DAAMS et al., (1999). Los asteriscos en la escal de tiempo CK95 indican la posición de nuevos posibles subcrones dentro de C5r (ABDUL AZÍZ 2001).

agreement with the chronology obtained from other spanish basins (GARCÉS *et al.,* 1996; KRIJGSMAN *et al.,* 1996).

The lower half of the Nombrevilla section is dominantly of reverse polarity and necessarily correlates to part of chron C5r. Short magnetozones N1 and N2 must represent subchrons, or even cryptochrons within C5r. However, correlation of such short magnetozones to the the time scale has to remain somewhat uncertain, since chances of missing short (less than 50 kyr) geomagnetic events are likely in our magnetostratigraphy considering the sampling time resolution of this study. In addition to this, CK95 geomagnetic polarity time scale (CANDE & KENT 1995) shows only two normal subchrons in C5r, but recent data (SCHNEIDER 1995; ABDUL AZIZ 2001) suggest that there are three or perhaps four sub/cryptochrons. This still awaits confirmation from other records.

Taking into account the uncertainty sources discussed above, two alternative correlations are illustrated in figure 4. Oldest option (N2 correlates with C5r.2n) gives an age for Nombrevilla 2of about 11.6 Ma. The younger option (N2 correlates with newly reported subchron C5r.1r-n (ABDUL AZIZ 2001) would give an age of 11.3 Ma. Further more conclusive constraints on the age of the Nombrevilla 2 locality could easily come from future studies in the neighbouring Toril section, where a downward extension of the magnetostratigraphy seems feasible.

DISCUSSION AND CONCLUSIONS

In the Calatayud-Daroca Basin, appearance of *Hipparion* was correlated with the lower boundary of small mammal local Zone H, which is characterised by the persistence of the *Megacricetodon gersii-ibericus* lineage and the appearance of *Hispanomys* (DAAMS, *et al.,* 1988; DAAMS *et al.,* 1999). The new detailed biostratigraphic work in the Nombrevilla area (PELÁEZ-CAMPOMANES *et al.,* 2000) has challenged this scenario, and shows that the replacement of *Cricetodon* by *Hispanomys* (Nombrevilla 9 and 10) was significantly older than the entry of *Hipparion* (Nom 1) in the Calatayud-Daroca basin. The magnetostratigraphic calibration of the Nombrevilla section yields an age of 11.1 Ma for the base of the Zone H, and shows a diachrony of 0.3-0.4 Myr with respect to the first occurrence of *Hipparion*. Consequently, the lower boundary of zone H does not correlate with, but preceeds the Aragonian/Vallesian boundary in the Daroca area (PELÁEZ-CAMPOMANES *et al.,* 2000).

The first occurrence of *Hipparion* in Nombrevilla correlates to the lower third of chron C5n and yields an interpolated age of 10.7-10.8 Ma. On the other hand, the youngest pre-*Hipparion* fossil record is dated to about 11.1 Ma. This is close to conflict with the age of the earliest *Hipparion* in theVallès-Penedès Basin which yielded a same age based on magnetostratigraphic correlation to chron C5r.1n. It must be admitted that this datum in the Vallès-Penedès is resulting a rare exception among the increasing data set of first occurrences of *Hipparion* in Eurasia near the base of C5n.2n at around 10.8 Ma. (WOODBURNE and SWISHER 1995). Since the first occurrence of *Hipparion* in the Vallès- Penedès was not strictly placed on, but laterally traced to the local magnetostratigraphic section (GARCÉS *et al.,* 1996), it is possible some inaccuracy in the location of the datum. This is not to say that the datum in the Vallès-Penedès is now proved to be incorrect, but in view of the increasing evidence of ages around 10.8 Ma of the *Hipparion* datum, further research would be necessary in order to confirm an older age.

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