

Supplementary Notes

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Long-period astronomical forcing of mammal turnover

This file contains information on age calibrations, treatment of age uncertainties and taxonomy, supplementary references and supplementary acknowledgements.

Stratigraphical-chronological framework

The stratigraphical-chronological framework for the 211 localities is shown in Supplementary Figure 1. Half of the localities are directly positioned in local magnetostratigraphically-dated sections or correlated to these sections lithostratigraphically on the basis of the lateral extension of beds. Another 25% of the localities are correlated litho- or biostratigraphically to local magnetostratigraphical records in the same basin. The ages of the remaining 25% localities are estimated using both intra- and extrabasinal age information. Details per stratigraphical interval are given below and in Supplementary Table 1.

Age uncertainties. We addressed the age uncertainties of the poorer constrained localities and of the first and last appearance datums by generating 1,000 equally probable, equally spaced (0.1 myr) time series for origination, extinction and turnover (= sum of origination and extinction) for the entire study interval. The final target series used consisted of the means of all 1,000 series. Each series is based on a combination of two types of random selection procedures of ages at the 0.01-myr level. 1) A procedure selecting from age uncertainty intervals of localities, for which the ages could not reliably be estimated at the 0.1-myr level on the basis of magneto- litho, and biostratigraphy. This resulted in 50 equally probable “age models” (series of 211 locality ages). Mean ages are given in Supplementary Table 1, and indicated in Fig. 3a of main article. 2) A procedure selecting from the uncertainty intervals preceding first appearances or succeeding last appearances (20 sets per age model, see next paragraph).

Procedure 1) was applied in three different ways. a) Random selection of ages from uncertainty intervals with maxima and minima determined by ages of the next older or younger localities (at 24-23, ~8.5, 6.5-5.5 Ma). b) Random selection from uncertainty intervals of biochronological values (tooth size of *Eucrietodon*) for ten Early Miocene localities. Only those linearly interpolated age series were included, which satisfied five constraints based on magnetostratigraphic/radiometric dating (at 22-19 Ma). In addition, corrections were applied to each series in order to be consistent with the local biozonation. c) Age series for nine localities (Ramblian type and Bañon sections, ~19-17.5 Ma) were calculated using linear lithostratigraphic interpolation between two calibration ages, the older one resulting from constrained biochronology (procedure b)

and the younger one from extrabasinal magnetostratigraphy/radiometric dating (France) and biostratigraphy. Details per stratigraphical interval are given below.

Sample size and uncertainty intervals. For each age model, we calculated uncertainty intervals (Supplementary Figs. 2-3) preceding first recorded occurrences and succeeding last recorded occurrences. The intervals were calculated on the basis of sample size and locality spacing. The probability of finding the lineage before (or after) its recorded presence was calculated using the proportion in the locality where it was first (or last) recorded¹. A lineage was considered absent when the cumulative probability of finding it over the preceding (succeeding) localities exceeded 80%². Next, the uncertainty intervals were extended conservatively across intervals without data up to the age of the next locality. These same procedures were applied to gaps in the record of lineages.

These were defined as true gaps, in case the midpoints of the uncertainty intervals differed more than 1.0 myr, in which case the lineage was split for the subsequent analyses. In other cases the lineage was assumed to have remained present (range-through approach). This procedure resulted in another 22 to 33 lineage segments depending on the age model. The corresponding lineages were considered to re-enter the record and were added to the initial 132 lineages. No true gap was defined for intervals > 1.0 myr without any localities. (Depending on the age model this situation sometimes occurs around 20 Ma).

Sample size effects on presence/absence were observed to be fairly small and further reduced by the range-through approach (Supplementary Figs. 4-5). Because the shape of the sample size histogram shows a tail after $n=1500$, very small proportions of less than $1/1500$ were considered as absence.

Testing for turnover. We tested for clustering of events by running separate bootstrap analyses for each of the 1,000 sets of origination, extinction and turnover. The observed numbers of events per moving 0.3-myr interval (the chosen bootstrap test statistic) were compared with the corresponding numbers of events of 1,000 rounds of reshuffling 0.1-myr level first and last appearance ages of all lineages across the presence intervals of their families³. The final significance levels (Supplementary Table 2) were calculated as the average significance level over the 1,000 sets, with each level calculated as the midpoint of the part of the cumulative probability distribution that corresponds to the observed number of events.

Upper Oligocene. Ages for the Upper Oligocene localities (Zones V-W) are based on the magnetostratigraphy of the Canales and Parrales sections⁴ and of Swiss sections^{5,6}, combined with a biostratigraphic ranking of Spanish and Swiss localities⁷.

Canales (Local Zone V, European Mammal Unit MP28, C7n, 24.3 Ma) and Vivel del Rio (both with *Pseudocricetodon cornelii*) are biochronologically bracketed by Fornant 7 (Switzerland, base C7n.2n, 24.4 Ma with *Pseudocricetodon incertus*) and Fornant 6 (top C7n.2n, 24.1 Ma, with *Adelomyarion vireti*). These species are considered to belong to one lineage^{7,8}. An age of 24.4 Ma was assigned to Vivel del Rio, because its fauna is considered slightly older than Canales⁷.

MP29 faunas can be split into faunas with and without *Rhodanomys*. The age of Hinojosa de Jarque (Zone V/W transition)⁹ belongs to the older part (which also contains

the Swiss locality Findreuse 18, C6r, 23.7 Ma), is younger than Fornant 6 (MP28, top C7n.2n, 24.1 Ma) and older than Parrales (middle part Zone W, top C6r, 23.4 Ma, younger part of faunas that correlate to MP29) and Brochener Fluh 19-20 (Switzerland, similar correlation to MP29, C6Cn3n, 23.3 Ma). The biostratigraphical position of Sayatón 1 (lower part Zone W, younger part of faunas correlated to MN29) is higher than that of Hinojosa but lower than that of Parrales (middle part Zone W, top C6r, 23.4 Ma). Sayatón 6 (upper part Zone W, with *Rhodanomys transiens*) can be positioned biostratigraphically between Parrales and Moncalvillo (Zone X, see below) and is younger than Findreuse 8 (C6Cn1r, 22.8 Ma, *R. aff. hugueneyae*). Moncalvillo (*R. schlosseri*, *Eucricetodon hesperius*) is younger than Boudry 2 (Switzerland, C6Cn.1r-1n, between 22.8 and 22.4 Ma, *R. transiens*). We assumed that it is younger than 22.4 Ma (age of Findreuse 6, with *E. collatus*?⁶).

Lower part of Lower Miocene (Zones X-Y). The construction of a composite section with Zone X-Y localities in the Loranca Basin is problematic, because the sections are distant from each other¹⁰. To estimate the ages of these localities while conforming to the randomisation approach used (see above), we generated random series of linear biochronological interpolations based on molar size increase¹¹. Series that did not adhere to the radiometric/paleomagnetic age constraints described below were rejected. We used the well-documented size increase in the late Oligocene – early Miocene evolutionary sequence *Eucricetodon dubius* – *E. collatus* – *E. hesperius* – *E. gerandianus* – *E. aquitanicus* – *E. infralactorensis*¹²⁻¹⁴ as our biochronological tool, and took the first principal component (PC1) of the M1, M2, m1 and m2 lengths as an age indicator. This indicator adequately reproduces a series of increasing biozone means (Zones V-W-X-Y1-Y2-Z). Next, a large number of PC1 series was generated based on randomly drawn lengths from the Student's t-distributions around the estimated means. In case of an inconsistency between locality age ranking and local zonation, localities were re-shuffled within the intervals of overlap. The numerical age constraints were the following: ages of 24.4 Ma for Vivel del Rio and 22.4 Ma for Parrales (see above), an age of 19.9 Ma separating younger and older Zone Y localities, a minimum age of 19.4 Ma for zone Y2, an age range of 17.7-17.2 Ma for Bañón 11A and a minimum duration of 1.0 myr for the combined Ramblian type and Bañón sections (see below).

The Y (= Y1+Y2) fauna of Tardienta (Ebro Basin)¹⁵ directly overlies a volcanic ash for which an age of 19.9 ± 0.3 Ma was inferred based on its correlation to and position in chron C6r¹⁶. This age is in agreement with the recalibration of the ³⁹Ar/⁴⁰Ar age of the original dating¹⁵ to 19.7 ± 0.3 Ma, using a recalibrated age of the HDB1 standard on the basis of the recently astronomically calibrated FCT standard¹⁷. Because Tardienta contains *Armantomys daamsi*, it is older than the Y2 localities and Buciegas (Y1), which contain the more advanced *A. parsani*, and younger than Cetina (Y1) which contains the more primitive *A. bijmai*.

Y2 localities are assumed to be older than the Swiss locality Goldinger Tobel 1 (“lower MN3a”, C6n, 19.4 Ma)¹⁸, which contains younger evolutionary stages of both *Ligerimys* and *Eucricetodon* (*L. antiquus* and *E. infralactorensis*).

Upper part of Lower Miocene (Zones Z-A). We estimated the age uncertainties of the localities from the Ramblian type and Bañón sections, which are tied to each other

lithostratigraphically, by linear interpolation using the biochronological estimates for the oldest locality Navarrete del Rio (see above) and the age estimates for the youngest locality Bañon 11A. The latter estimates are constrained by a correlation to chron C5Dn (17.24-17.53 Ma) of the French fauna Beaulieu based on a normal magnetic polarity and a radiometric date of 17.5 ± 0.3 Ma¹⁹. The fauna of Beaulieu is very similar to that of Bañon 11A showing the same evolutionary stage of *Ligerimys* and the presence of the rare *Pseudotheridomys fejfari*. We allowed a maximum age of 17.7 Ma for Bañon 11A, and a minimum age of 17.2 Ma based on the absence of *Democricetodon*, which entered the Swiss record no later than 17.2 Ma¹⁸.

Finally, we specified a minimum age duration of 1.0 myr for the interval between Navarrete del Rio and Bañon 11A. Because of the age of a volcanoclastic layer, which was interpreted as the equivalent of the volcanic ash of 19.9 Ma described above²⁰, a shorter duration is unlikely.

Uppermost part of the Lower Miocene and Middle Miocene (Zones B-G). The Middle Miocene part of the record (Zone C-G) is paleomagnetically constrained in the Daroca area. Ages for Zone B and lower Zone C localities were estimated by downward lithostratigraphic extrapolation in the parallel sections of Olmo Redondo-San Roque^{21,22}.

Lower-middle part of the Upper Miocene (Zones G-K). The ages of the Zone G-H localities were paleomagnetically constrained in the Nombrevilla section near Daroca^{23,24}, to which we litho- and biostratigraphically correlated the nearby faunas of Toril, Carrilanga and Pedregueras.

The Upper Miocene Zone I-K localities are situated in the Teruel Basin. Magnetobiostratigraphic correlations²⁵⁻²⁸ have been slightly modified and refined on the basis of cyclostratigraphy²⁹. A consistent age model for Zone J was derived using additional paleomagnetic sampling in the Masada Ruea section (north of Teruel), for which the re-interpreted magnetostratigraphy results in an estimate of 8.9 Ma for the top of the basin-wide capping limestone unit, for which an almost similar estimate of 8.96 Ma was inferred in the section of Cascante (south of Teruel) on the basis of cyclostratigraphy²⁹.

An age of 8.75 Ma was estimated for the basal Zone K fauna Patrimonio Forestal 5 (containing *Huerzelerimys minor*, *H. vireti* and *Parapodemus gaudryi*) by upward cyclo- and lithostratigraphic extrapolation in the Cascante composite section. Three slightly older faunas (Peralejos D, Cascante-Cubla 1,2) belong to a new subzone J4, which we define as the *Parapodemus lugdunensis*-*Huerzelerimys vireti* subzone: from the entry of *Parapodemus lugdunensis* to the entry of *Huerzelerimys vireti*. In addition, the J4 base characterized by the entry of *Eozapus intermedius*. We re-define Zone K²⁷ as the *Huerzelerimys vireti* Zone defined by the total range of *Huerzelerimys vireti* (instead of the *Parapodemus lugdunensis* Zone).

Upper part of the Upper Miocene (Zones L-M). Previously estimated zone L and M locality ages²⁷ for the Teruel Basin were slightly modified, because more localities were included in the biochronological interpolation procedure that uses size increase in *Occitanomys adroveri*. These estimates were combined with magnetostratigraphical (Bunker section, K-L boundary in Cabriel Basin, E. Spain), lithostratigraphical (Masada

del Valle and Tortajada sections) and updated biochronological constraints (morphological change in the *Progonomys hispanicus* - *O. sondaari* lineage)²⁷.

Zone M locality ages were estimated using magnetostratigraphical constraints for M1 localities in the Bunker section and for the L-M and M2-M3 boundaries (*Paraethomys* entry) on the basis of sections in the Fortuna basin^{27,30}.

Uppermost Miocene and Pliocene (subzone M3 and higher). Pliocene localities (Teruel Basin) younger than 4.5 Ma were tied to the numerical timescale by first-order paleomagnetic correlations^{31,32}. The top of the *Trilophomys* (Tr) subzone is constrained in de Villalba Alta section. This zone is included in the Celadas composite and Lomas de Casares sections³³, which contain localities from Zone L up to the archaic *Mimomys* subzone (aM). The assumption of constant sedimentation rates yields a maximum age constraint of 5.3-5.0 Ma for the entry of *Promimomys* (recorded in Celadas 9 and 12). As this entry has been dated in Greece at 5.3 Ma^{17,34} we opted for the maximum age model. The fauna of Fuente del Viso (Southern Spain) is paleomagnetically dated at 4.9 Ma^{31,32}, but its species content does not allow a more precise biostratigraphic correlation than either the *Celadensia* (Ce) subzone or the subzone with two *Paraethomys* and *Promimomys* (PP). Finally, we used a maximum age constraint of 6.0 Ma (paleomagnetic age for the M3 fauna of Venta del Moro, Cabriel Basin)³¹ for the locality Lomas de Casares 3 (base *Celadensia* subzone).

Taxonomy

The rodent (Rodentia) database consists of published (main references 7, 10, 22, 27, 33) and unpublished lists and specimen counts. The number of lineages analysed depends on the number of re-entries, which, in turn, depends on the age model used. The following list pertains to an intermediate age model yielding the mean number of lineages (159), and corresponds to the ranges plotted in Supplementary Fig. 2. Numbers in brackets indicate the first, second, etc. lineage segment in case of re-entries.

1= *Eomys majori*, 2= *Microdyromys praemurinus*, 3= *Gliravus bravoii*, 4= *Eomys zitteli*, 5= *Melissiodon chaticus*, 6= *Plesiosminthus promyaron* – *P. myarion*, 7= *Archaeomys laurillardi*, 8= *Pseudocricetodon adroveri* – *P. thaleri*, 9= *Eomys alulghensis*, 10= *Gliravus bruijini*, 11= *Bransatoglis fugax*, 12= *Archaeomys intermedius*, 13= *Archaeomys* (*Rhombarchaeomys*) sp., 14= *Issiodoromys limognensis* – *I. pseudanaema*, 15= *Eomys huerzeleri*, 16= *Plesiosminthus moralesi* – *P. schaubi* (1), 17= *Pseudocricetodon cornelii* – *Adelomyarion vireti* – *A. alberti*, 18= “*Sciurus*” *costatus*, 19= “*Sciurus*” sp., 20= *Vasseuromys autolensis*, 21= *Plesiosminthus moralesi* – *P. schaubi* (2), 22= *Columbomys agustii*, 23= *Glirudinus glirulus*, 24= *Heteroxerus paulhiacensis*, 25= *Eucricetodon cetinensis* (1), 26= *Steneofiber eseri*, 27= *Pseudodryomys lopezae*, 28= *Altomiramys daamsi* (1), 29= *Glirudinus modestus* (1), 30= *Paleosciurus feignouxii* (1), 31= *Heteroxerus lavocati* (1), 32= *Prodryomys brailloni*, 33= *Praearmantomys crusafonti* (1), 34= *Rhodanomys hugueney* – *R. transiens* – *Rittenaria schlosseri* – *R. molinae* – *R. manca*, 35= *Aragoxerus ignis*, 36= *Eucricetodon cetinensis* (2), 37= *Heteroxerus lavocati* (2), 38= *Paleosciurus feignouxii* (2), 39= *Altomiramys daamsi* (2), 41= *Eucricetodon dubius* – *collatus* – *hesperius* – *E. gerandianus* – *E. sp.* – *E. aff. aquitanicus* – *E. aff.*

infralactorensis - *E. ex aquitanicus/infralactorensis*, 42= *Ligerimys fahlbuschi*, 43= *Ligerimys magnus*, 44= *Pseudotheridomys lacombai* - *Ligerimys antiquus*, 45= *Pseudotheridomys fejfari*, 46= *Heteroxerus lavocati* (3), 47= *Melissiodon dominans*, 48= *Paleosciurus* sp., 49= *Rutufa?* sp., 50= *Ligerimys palomae*, 51= *Ligerimys florancei*, 52= *Praearmantomys crusafonti* (2), 53= *Glirudinus undosus* (1), 54 = *Pseudodryomys julii*, 55= *Glirudinus modestus* (2), 56= *Pseudodryomys robustus*, 57= *Peridyromys darocensis* - *sondaari*, 58= *Ligerimys ellipticus*, 59= *Peridyromys murinus* (incl. *P. columbarii*) (1), 60= *Prodryomys* sp., 61= *Heteroxerus* sp.1, 62= *Petauristinae* gen. sp. (1), 63= *Megacricetodon* n. sp., 64= *Spermophilinus besana* - *S. bredai* - *S. turoliensis* (1), 65= *Atlantoxerus blacki* - *A. sp.* (1), 66= *Peridyromys murinus* (2), 67= *Armantomys bijmai* (- *A. daamsi*) - *A. parsani* - *A. jasperi*, 68= *Microdyromys* n. sp., 69= *Eumyarion* sp. 70= *Keramidomys* sp., 71, 72= *Pseudodryomys simplicidens*, 73= *Peridyromys rex*, 74= *Pseudodryomys ibericus*, 75= *Democricetodon hispanicus* - *D. decipiens* - *D. moralesi* - *D. jordensi* - *D. lacombai*, 76 = *Megacricetodon collongensis*, 77= *Paragilirulus werenfelsi*, 78= *Heteroxerus rubricati* - *H. mariatheresae*, 79= *Heteroxerus* n. sp. 2, 80= *Armantomys aragonensis* - *A. tricristatus*, 81= *Megacricetodon rafaelli*, 82= *Microdyromys complicatus* (1), 83= *Bransatoglis* sp., 84= *Tempestia ovilis* - *T. hartenbergi* (1), 85= *Microdyromys koenigswaldi*, 86= *Democricetodon gaillardi*, 87= *Eomyops catalaunicus*, 88= *Megacricetodon gregarius*, 89= *Eliomys truci*, 90= *Myoglis meini*, 91= *Paragilirulus werenfelsi*, 92= *Democricetodon sulcatus* (1), 93= *Microdyromys complicatus* (2), 94= *Glirudinus undosus* (2), 95= *Spermophilinus besana* - *S. bredai* - *S. turoliensis* (2), 96= *Megacricetodon gersii* - *M. crusafonti* - *M. ibericus*, 97= *Cricetodon jotae* - *Hispanomys nombrevillae*, 98= *Democricetodon franconicus* - *D. koenigswaldi* - *D. larteti* - *D. crusafonti*, 99= *Microdyromys legidensis*, 100= *Megacricetodon minor* - *M. debruijini*, 101= *Myomimus dehmi*, 102= *Tamias* sp., 103= *Hispanomys* aff. *peralensis*, 104= *Democricetodon sulcatus* (2), 105= *Muscardinus thaleri* - *M. hispanicus* - *M. aff. hispanicus* (1), 106 = *Cricetulodon hartenbergi*, 107= *Ramys multicristatus*, 108= *Chalicomys* sp., 109= *Atlantoxerus blacki* - *A. sp.* (2), 110= *Tempestia ovilis* - *T. hartenbergi* (2), 111= cf. *Eumyarion* sp., 112= *Myomimus* sp. A, 113 = *Progonomys cathalai* - *Huerzelerimys minor*, 114= *Heteroxerus grivensis*, 115= *Parapodemus lugdunensis* - *Apodemus dominans* (1), 116= *Eliomys* sp. A., 117= *Kowalskia occidentalis*, 118= *Eozapus intermedius* - *E. janossyi* (1), 119= *Progonomys hispanicus* - *Occitanomys sondaari* - *O. adroveri*, 120= *Huerzelerimys vireti* - *H. turoliensis*, 121= *Occitanomys* sp. A, 122= *Hispanomys* sp. A., 123= *Parapodemus barbarae*, 124= *Atlantoxerus adroveri* - *A. margaritae* (1), 125= *Muscardinus thaleri* - *M. hispanicus* - *M. aff. hispanicus* (2), 127= *Murinae* indet., 128= *Castromys inflatus* (1), 129= *Dipoides problematicus* - *D. sigmodus*, 130= *Blancomys sanzi* - *B. neglectus* - *B. meini* (1), 131= *Micromys paricioi*, 132= *Kowalskia intermedia*, 133= *Celadensis nicolae*, 134= *Eozapus intermedius* - *E. janossyi* (2), 135= *Promimomys insuliferus*, 136= *Paraethomys anomalus*, 137= *Castromys inflatus* (2), 138= *Apocricetus aff. plinii* - *A. plinii* - *A. alberti* - *A. barrieri*, 139= *Rhagapodemus* sp. (1), 140 = *Occitanomys alcalai*, 141= *Blancomys sanzi* - *B. neglectus* - *B. meini* (2), 142= *Paraethomys abaigari*, 143= *Paraethomys meini*, 144= *Hystrix depereti*, 145= *Atlantoxerus adroveri* - *A. margaritae* (2), 146= *Parapodemus gaudryi* - *Apodemus gudrunae* - *A. gorafensis*, 147= *Eliomys intermedius*, 148= *Hispanomys aragonensis* - *H. aragoniensis* - *H. peralensis* - *H. freudenthali* - *Ruscinomys schaubi* - *R. lasallei* - *R. europeus*, 149= *Rhagapodemus*

(2), 150= *Petauristinae* gen. sp. (2), 151= *Eliomys truci*, 152= *Trilophomys castromys-vandeweerdii*, 153= *Occitanomys brailloni*, 154= *Mimomys gracilis* – *M. stehlini*, 155= *Stephanomys ramblensis* – *S. dubari* – *S. medius* – *S. margaritae* – *S. vandeweerdii* – *S. minor* – *S. prietaensis* – *S. balcellsii* – *S. progressus*, 156= *Dolomys adroveri* – *Kislangia ischus*, 157= *Castillomys gracilis* – *C. crusafonti* – *C. rivas*, 158= *Mimomys davakosi* – *M. occitanus* – *M. hajnackensis*, 159= *Parapodemus lugdunensis* – *Apodemus dominans* (2).

Supplementary References and Notes

(including references referred to in Supplementary Tables and Supplementary Figures)

1. The probability p of finding the taxon is given by $p = 1 - (1-q)^r$ with q = the proportion of the taxon in the locality where it was first (or last) recorded, and r = the additional number of specimens sampled. In rare cases where locality sample size was very low ($n < 10$), we based q on the sum of this and the next older/younger locality. Similar calculations were applied to fossil faunas before², but with q taken from the complete range of the taxon.
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