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European Neogene mammal chronology: past, present and future

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The complex history of European Neogene mammal chronology is reviewed. Resulting in an a posteriori classification of systems into a stratigraphic and a faunal 'school of thought'. The divergence of opinions on stratigraphic/chronologic matters, which has continued up to the present day, can largely be attributed to the specific nature of the mammal record, which is characterized by a relatively poor degree of stratigraphic control, by large sampling errors, and by a considerable degree of both provinciality and diachrony. A solution is proposed in the form of a dual system, on the one hand based on the dense and well-calibrated Spanish record, and on the other hand on a system of European reference localities. The reference localities could be discrete levels on an ordinal scale or boundaries on a continuous faunal scale. Local calibrations and quantitative interpolation techniques (using as much faunal information as possible) should be used to tie the European locality scale to the Spanish mammal zonation.

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INTRODUCTION

European mammal paleontologists and stratigraphers have attempted to establish formal continental stratigraphic/chronologic systems for almost four decades. Opinions have diverged, however, on the question how such mammal-based systems should be defined. Particularly for the Neogene this has lead to the unfortunate situation where several European continental stratigraphic/chronologic systems, based on different philosophies, have existed (and still exist) side-by-side, even under the same names. Such a divergence of opinions has never occurred among marine workers, when constructing their stratigraphic/chronologic systems on similar geographic scales.

Why is it so difficult to construct a straightforward mammal-based system? The explanation seems to be at least threefold: (1) the nature of the mammal record is very different from that of most marine organisms; (2) there is a lack of calibrations of mammal-bearing sediments to the numerical time scale (partly a consequence of (1)); (3) there is a legacy of different stratigraphic/chronologic philosophies, terminologies and definitions, which have confounded subsequent discussion.

(1) Whereas, for instance, marine microplanktonic organisms can be relatively easily recovered in large numbers from numerous stratigraphic levels in cores and land-based sections, well-documented mammal localities are scarce and not seldom with-out (basin-level) lithostratigraphic context. Even dense micromammal successions (e.g., those from Spain) are much lower in resolution than the typical marine microplanktonic successions

used for zonations. The low resolution of mammal sequences results in large uncertainty intervals with regard to bioevents. In addition, the biogeographic patterns in terrestrial mammals are more complex than that of most marine organisms, because terrestrial ecology is more heterogeneous spatially, resulting in higher degrees of provinciality and diachrony (see below).

(2) More and more local calibrations of continental sections to the geomagnetic polarity time scale are now being established. However, because of the strong provinciality of mammal faunas, many more are needed in order to correlate regions.

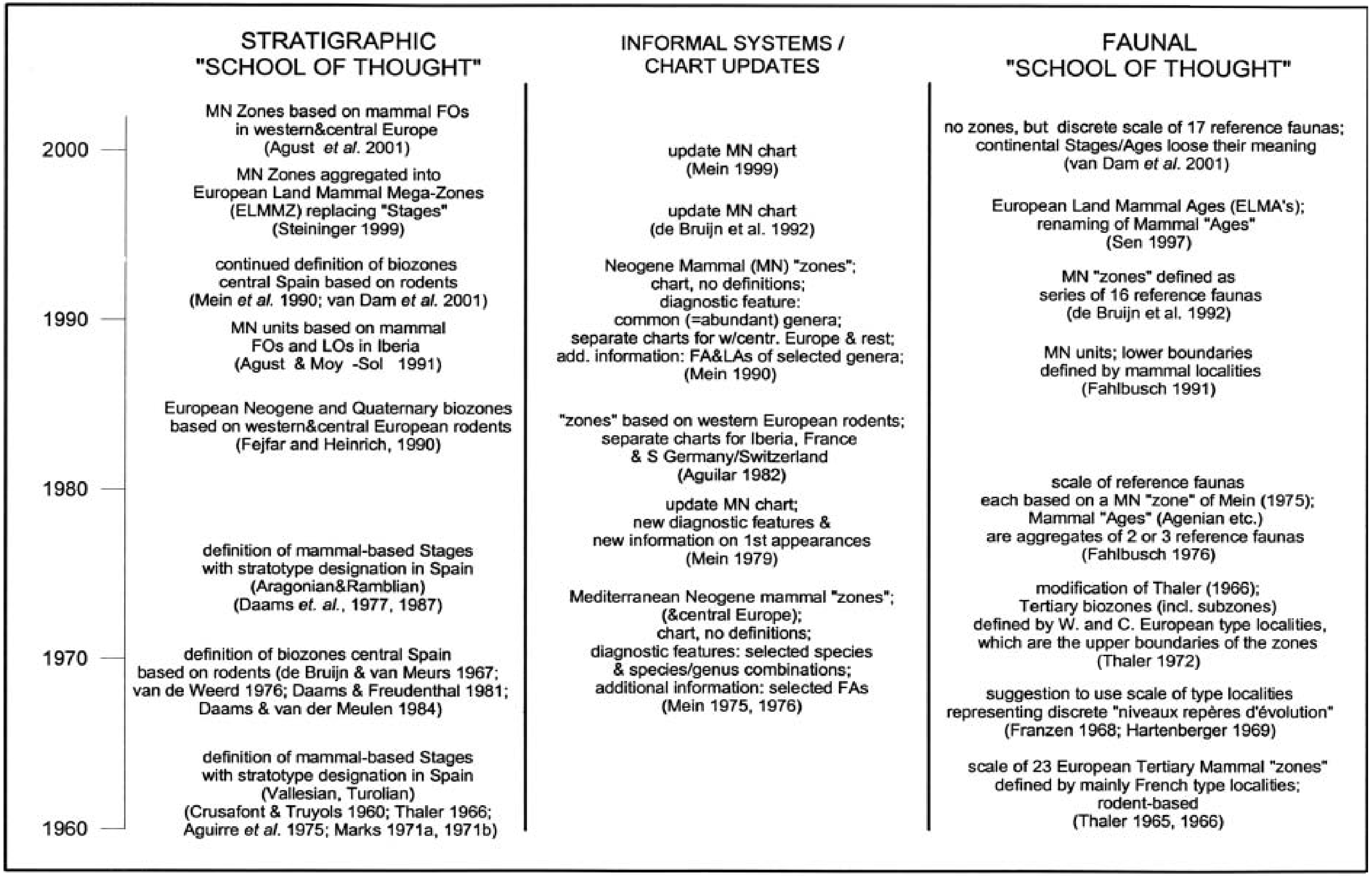
(3) A large part of the confusion surrounding European mammal-based chronological systems is due to the use of different philosophies and definitions (Fig. 1). After reviewing the literature on this subject, I have classified systems, proposals and opinions as belonging to either one or the other of two ‘schools of thought’: stratigraphic and faunal. A third series of works, the backbone of which consists of the various chart updates of Pierre Mein and others, do not fit either of these approaches, because these do not contain formal definitions of units and/or boundaries. These charts can be regarded as informal systems and sources of information on the basis of which workers of the other two approaches have constructed their formal systems. Hans de Bruijn has played a crucial role in the development of European (and Eurasian) continental biostratigraphy and -chronology. His contribution to this field has been (and still is) both practical, by generating a continuous input of new data, as well as conceptual, by being a driving force in the shaping and maintaining of the stratigraphic/chronologic systems themselves. A recent proposal of Hans to bring new light into the dark will be discussed and elaborated in this paper.

TWO ‘SCHOOLS OF THOUGHT’

The stratigraphic approach conforms to the strict biostratigraphic and chronostratigraphic/geochronologic principles as stated in the international stratigraphic guides (e.g., Salvador 1994). The biozones, and the chronozones based on them, are rock-based. Chronostratigraphic units (e.g., Stages) have geochronologic equivalents (e.g., Ages) and are defined by boundary-stratotypes in the field (recently, type sections have lost the status of being valid stratotypes; Salvador 1994). The advantage of a formal stratigraphic approach is the straightforward assignment of localities to biozones, especially in case they are defined on the basis of ranges of one or two taxa. The method works well for local mammal sequences. However, on larger geographic scales the practical value of the biozones and their chronostratigraphic equivalents (including Stages) gets more and more limited, which is due to provinciality, diachrony and sampling error (see below).

The faunal approach is based on complete assemblages, and typically implies the construction of a system of time-ordered (reference) localities. These localities correspond to certain stages of faunal evolution (‘niveaux repères’). The advantage of the faunal approach is the definition of well-documented, exact points in time (the localities). The disadvantage is a less straightforward correlation to the reference localities: a large amount of faunal information has to be considered, and somehow averaged and weighted properly.

Figure 1 to shows the most important steps in the ‘evolution’ of European Neogene mammal stratigraphy and chronology during the last fifty years (for historical reviews, see also Berggren & Van Couvering 1974, Lindsay & Tedford 1990, Mein 1999a). Initially, European mammal paleontologists felt the need to define continental counterparts of the marine chronostratigraphic/geochronologic units (Stages/Ages), because at that time there were no reliable correlations between marine and continental biozones. These early-proposed units (going back to the



STRATIGRAPHIC "SCHOOL OF THOUGHT"

MN Zones based on mammal FOs in western&central Europe (Agust *et al.* 2001)

MN Zones aggregated into European Land Mammal Mega-Zones (ELMMZ) replacing "Stages" (Steininger 1999)

continued definition of biozones central Spain based on rodents (Mein *et al.* 1990; van Dam *et al.* 2001)

MN units based on mammal FOs and LOs in Iberia (Agust & Moy -Sol 1991)

European Neogene and Quaternary biozones based on western&central European rodents (Fejfar and Heinrich, 1990)

definition of mammal-based Stages with stratotype designation in Spain (Aragonian&Ramblian) (Daams *et. al.*, 1977, 1987)

definition of biozones central Spain based on rodents (de Bruijn & van Meurs 1967; van de Weerd 1976; Daams & Freudenthal 1981; Daams & van der Meulen 1984)

definition of mammal-based Stages with stratotype designation in Spain (Vallesian, Turolian) (Crusafont & Truyols 1960; Thaler 1966; Aguirre *et al.* 1975; Marks 1971a, 1971b)

INFORMAL SYSTEMS / CHART UPDATES

update MN chart (Mein 1999)

update MN chart (de Bruijn et al. 1992)

Neogene Mammal (MN) "zones"; chart, no definitions; diagnostic feature: common (=abundant) genera; separate charts for w/centr. Europe & rest; add. information: FA&LAs of selected genera; (Mein 1990)

"zones" based on western European rodents; separate charts for Iberia, France & S Germany/Switzerland (Aguilar 1982)

update MN chart; new diagnostic features & new information on 1st appearances (Mein 1979)

Mediterranean Neogene mammal "zones"; (&central Europe); chart, no definitions; diagnostic features: selected species & species/genus combinations; additional information: selected FAs (Mein 1975, 1976)

FAUNAL "SCHOOL OF THOUGHT"

no zones, but discrete scale of 17 reference faunas; continental Stages/Ages loose their meaning (van Dam *et al.* 2001)

European Land Mammal Ages (ELMA's); renaming of Mammal "Ages" (Sen 1997)

MN "zones" defined as series of 16 reference faunas (de Bruijn et al. 1992)

MN units; lower boundaries defined by mammal localities (Fahlbusch 1991)

scale of reference faunas each based on a MN "zone" of Mein (1975); Mammal "Ages" (Agenian etc.) are aggregates of 2 or 3 reference faunas (Fahlbusch 1976)

modification of Thaler (1966); Tertiary biozones (incl. subzones) defined by W. and C. European type localities, which are the upper boundaries of the zones (Thaler 1972)

suggestion to use scale of type localities representing discrete "niveaux repères d'évolution" (Franzen 1968; Hartenberger 1969)

scale of 23 European Tertiary Mammal "zones" defined by mainly French type localities; rodent-based (Thaler 1965, 1966)

Figure 1 Selected events in the history of European Mammal Neogene chronological systems from the nineteensixties onwards. Philosophies, proposals, and opinions have been classified into two formal approaches indicated as stratigraphic and faunal 'schools of thought', and a pragmatic, informal approach, responsible for chart updates on the basis of a mix of seven characters.

19th century, e.g., the Oeningian) were not defined on the basis of stratotypes, however. During the 1950s and 1960s various workers started to take a formal stratigraphic approach. The first formal definitions of Continental Stages with stratotype designations in Spain were published (Vallesian, Turolian; Crusafont & Truyols 1960, Thaler 1966). This work was continued during the 1970's and 1980's (Aragonian, Ramblian, also Spain; Daams *et al*. 1977, 1987). Already from the 1960's onwards (de Bruijn & van Meurs 1967) smaller biostratigraphic units based on rodent ranges were defined locally (Central Spain), which finally has lead to a complete Neogene zonation in this region (van de Weerd 1976, Daams & Freudenthal 1981, Daams & van der Meulen 1984, Mein *et al.* 1990, van Dam *et al*. 2001).

Recently, biostratigraphic schemes combining the better-dated (rodent and large mammal) entries from different Spanish basins have been proposed (Agustí & Moyà-Solà 1999, Agustí *et al*. 2001). However, by calling their units 'MN' units or zones the latter authors suggest that these local/regional zones can be recognized all over Europe, which is generally not the case. Continent-wide application is also suggested by the 'European' biozonation scheme of Fejfar & Heinrich (1990), who also base their system on local rodent ranges, in this case from different regions.

Thaler (1965, 1966, 1972) pioneered the faunal approach, and constructed his scale of European Tertiary Mammal 'zones' defined by type localities. His first system consisted of 23 Tertiary units named after localities, some of which were later divided into subunits. Apart from this system, which was mainly based on evolutionary stages in rodents, Thaler (1972) also proposed another faunal system based on faunal breaks ('*Anchiterium* Zone', '*Hipparion* Zone', etc.).

Many more data were used by Mein (1975, 1976) in the construction of his MN (Mammal Neogene) charts. Mein used various features such as the presence of selected taxa and first appearances to *characterize*, but not formally define the MN 'zones'. Although inspired by Blow's (1969) system of numbered planktonic foraminifer (NP) zones (note that MN zones started off as 'NM' zones), Mein did not define the zones formally after taxon names as Blow had done. Neither did he intend to follow Thaler in using reference localities to define the Zones. It was afterwards, during the International Symposium on mammalian stratigraphy of the European Tertiary in Munich (1975), that reference localities were attached to the MN units (Fahlbusch 1976). Mein himself regarded the status of the reference localities more like an *illustration* rather than a definition of the MN units (Mein 1990, p. 90). The intention to have a chronologic tool rather than a formalized system explains why criteria were modified and why geographic subdivisions were applied (Mein, 1979, 1990, 1999b). The system of Aguilar (1982) was constructed in the same spirit as Mein's, given the loose definition of boundaries and groupings of taxonomically dissimilar, geographically separated assemblages into one 'zone'.

An unfortunate development took place when the designation 'MN' was adopted for differently defined systems. On the one hand, Agustí and coworkers (1991, 2001) defined true biozones on the basis of predominantly Spanish small and large mammal FO's and LO's and called these MN Zones, thereby implying continent-wide application. Also, Steininger (1999) adopted the MN terminology to propose formal biostratigraphic units (leaving open their exact definition to others). In addition, Steininger proposes to combine the zones into larger units: European Land Mammal Megazones (ELMMZ: Orleanean, Vallesian etc.).

The participants of the Munich Symposium (1975), on the other hand, had agreed upon the explicit linking of MN units to reference localities (Fahlbusch 1976). This approach was further formalized by de Bruijn *et al.* (1992), who explicitly defined the MN units as the reference localities themselves, thereby achieving consistency with the Paleogene system of MP reference levels (Schmidt-Kittler 1987). Doing this, de Bruijn *et al.* (1992) formalized earlier suggestions (Franzen 1968, Hartenberger 1969) to subdivide continuous faunal evolution by discrete points. The implication is that a fauna can only be correlated with one of 16 values of the MN scale and not to values in between, the rationale being that the inaccuracy of long-distance, continent-wide correlations on the basis of faunal information alone does not allow higher resolutions (van Dam *et al.*, 2001).

In order to be consistent with the definition of 16 discrete MN 'values' (rather than intervals), larger units such as defined in Fahlbusch (1976) (Orleanean 'Ages', etc.) also would have to be transformed to non-continuous units, i.e. aggregates of two or three discrete MN reference faunas. For example, the 'Vallesian' would solely consist of a pair of two local reference faunas: Can Llobateres and Masía del Barbo (van Dam *et al*. 2001). Such an extreme view was not taken by the participants of the Munich symposium (1975), who regarded the Mammal Ages as spans of time representing faunal episodes, an interpretation similar to the classic meaning of North American Land Mammal Ages (NALMA) as defined by Wood *et al.* (1941). In the same spirit, the name 'European Land Mammal Ages' (ELMA) was coined to conceptually cover the larger European faunal units (Sen 1997). (Note that parts of the discussions on European mammal-based chronological systems are very similar to those on North American systems, for instance concerning the status of the NALMAs [see Lindsay & Tedford 1990, Walsh 1998] and delineation of faunal units [see Alroy 1992]).

Is it possible to define sharp boundaries using the faunal approach? By definition, an ordinal scale of units such as the one proposed by de Bruijn *et al.* (1992) does not contain boundaries. Nevertheless, an alternative solution is possible (Thaler 1972, Fahlbusch 1976, 1991, see also Sigé & Legendre 1997), defining boundaries in the reference localities themselves (the 'golden spikes' of continental stratigraphy; Fahlbusch 1991), thereby creating continuous units consisting of a segment of faunal evolution. One might object that such segments do not correspond to natural units separated by faunal breaks. There are no clear indications, however, that such natural units of relative short duration (~1 Myr) actually exist on a continental scale (see below). Apart from this, it is quite defendable not to confound geological aspects (chronology) with biological aspects (faunal dynamics).

The use of complete faunas instead of single-taxon events for long-distance correlation is perfectly in line with recent advances made in multivariate interpolation methods that have optimal calibration of mammal localities as their goal (Alroy 1992, 1994, Legendre & Bachelet 1993, Alroy *et al*. 1998). Such methods are powerful, because mammal assemblages contain a large amount of temporal information in their faunal composition and size/morphology structure. Attempts have even been made to 'calculate' mammal-based chronological units as time-ordered clusters of faunas on the basis of such multivariate methods (Alroy 1992, Azanza *et al*. 1997). This results in systems the boundaries of which may change after adding new taxon-locality information. This could be an argument for using the interpolation methods only for temporal scaling of localities and not for constructing chronological systems.

PROVINCIALITY

Provinciality and endemism are serious handicaps for establishing a reliable system of European mammal-based chronology. It has been known for a very long time that large faunal differences exist within Europe, e.g. during the late Miocene (Gaudry 1865, 1873, see also Tobien 1967, Bernor 1984, Bernor *et al*. 1996). For this interval, a faunal overlap across Europe of only 15-30% for species and slightly higher for genera is normal (van Dam *et al*. 2001). This situation is in striking contrast with that of the marine record. The Messinian offers an extreme example: whereas the two well-described mammalian faunas of El Arquillo, Spain (MN13 reference locality) and Maramena (Greece) do not have a single documented species in common, Messinian planktonic foraminifer faunas from the Sorbas Basin, Spain and from Crete, Greece show a 100% overlap (F.J. Sierro, pers. comm. 2001, W.J. Zachariasse, pers. comm. 2002).

DIACHRONY

It has become more and more clear that mammal events are highly diachronous across continents. A recent analysis on North American mammals (Alroy 1998) has shown that species-level diachrony between the western Interior and West coast averages about 2 Myr for both immigrants and non-immigrants. Mean diachrony reduces after performing a general correction for under-sampling, but still amounts to 0.5 Myr for immigrants and 0.9 Myr for non-immigrants.

Isochrony is not expected to be a common feature of mammal dispersal across large areas, even when differences smaller than 0.1 Myr are ignored. I can imagine three 'end-member' models of faunal distribution in space and time at the spatial scale of a continent (such as Europe) and the temporal scale of 1-2 Myr (Fig. 2). All assume a high degree of provinciality. Additionally, model 1 assumes (a) isochrony of all species FO's and LO's and (b) their concentration in faunal turnover events with coordinated stasis (Brett & Baird 1995) between the events. This model is not realistic, because in order to regularly and synchronously disrupt geographically separated faunas with different compositions, a frequent occurrence of strong large-scale external tectonic and/or climatic perturbations would be required. Such events have occurred occasionally (e.g. during the Eocene/ Oligocene transition), but certainly not with a frequency in the order of 1 Myr.

In model 2 the coordinated stasis condition is relaxed, but isochrony is still assumed for all taxa. Also this model should be regarded as unrealistic. In my opinion, geologically isochronous dispersal is expected to occur only when a taxon invades an entirely new ecological system (typically after transcontinental migration) by occupying a major vacant niche or rapidly out-competing other species with a key innovation.

Model 3 assumes absence of both coordinated stasis and isochrony. This model is probably closest to reality: the chances that the dispersal of an occasional widespread species (the elongated thick line in the upper part of Fig. 2) is isochronous, may be regarded as small.

An associated problem concerns sampling.

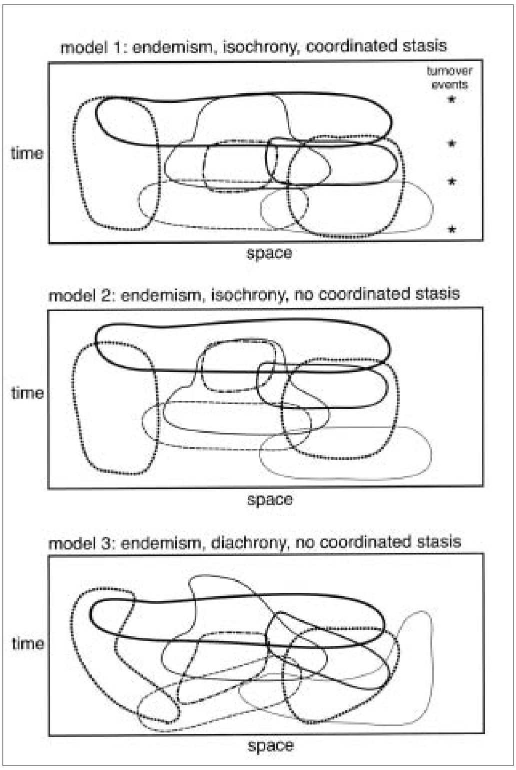


Figure 2 Three theoretical models of mammal faunal distributions in space and time at the spatial scale of a continental and the temporal scale of 1-2 Myr. All three models assume high and similar degrees of endemism, but differ in the degree of diachrony and coordinated turnover/stasis.

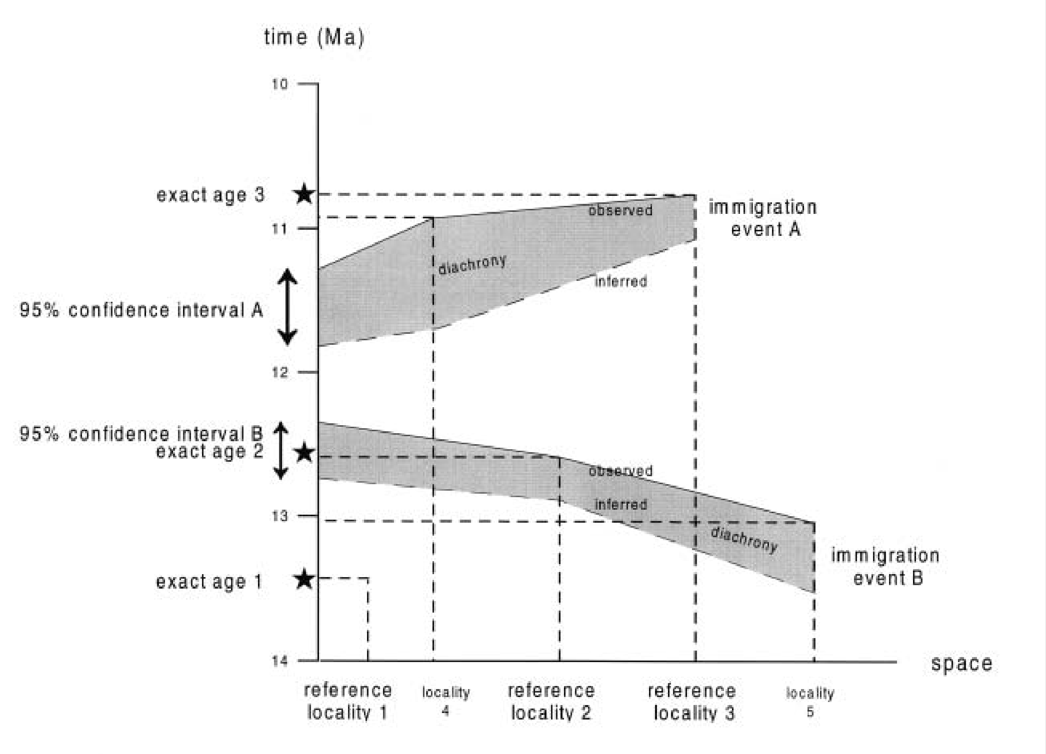


Figure 3 Hypothetical time-space diagram (time axis: several Myr; space axis: continent) showing the uncertainties in the timing of mammal immigration events due to diachrony and sampling. No such uncertainties are associated with localities, which constitute a more exact basis for the definition of continental chronological units.

As noted above, mammal localities are essentially scarce. Even in the well-sampled Late Miocene Siwalik succession of North Pakistan, many first and last occurrences have confidence intervals of 0.5 Myr or higher (Barry *et al*. 2002). Furthermore, species might be present in low numbers before they expand to numbers large enough to be documented. The problem worsens with increasing study areas. Even in relatively well-studied cases such as the dispersal of *Hipparion* in the Old World (Garcés *et al*. 1997) and *Progonomys* in Europe (van Dam *et al.* 2001) one cannot go much further down than to resolutions of 0.5 Myr.

In short, the inaccuracy associated with an immigration event across the continent, consisting of both the true diachrony and sampling error, may easily exceed half a million of years and approach the duration of the MN units themselves (as illustrated in Figure 3). Such large inaccuracies are in striking contrast to results for the marine Mediterranean, where late Neogene entries and exits of planktonic foraminifers have been demonstrated to be exactly isochronous, i.e. within the duration of precession cycles (20,000 yr) (Krijgsman *et al.* 1999). Unlike the first or last occurrence of an immigration event, there is no diachrony and almost no sampling error associated with the chronological position of a locality (Fig. 3). In this sense, a chronological system of localities is ‘exact’. Obviously, there are uncertainties associated with the correlation of the reference localities to the numerical time scale and with the correlation of particular localities to the system of reference localities. However, quantitative methods using large amounts of faunal information will reduce these errors (see below).

PROPOSAL FOR A DUAL SYSTEM

At this point, the following question should be asked: what is the use of presenting zone boundaries if the ‘internal’ age uncertainties (i.e. the errors other than those related to calibration) of the boundaries may approach the duration of the zones? Such a representation is misleading for workers both inside and outside mammal paleontology. In my opinion, the best solution for the European Neogene would be a *dual scheme* consisting of a system of European reference localities, which is optimally tied to the well-calibrated Spanish mammal zonation. During the last meeting of the ESF-EEDEN project in Sabadell, Spain, Hans de Bruijn has presented a note with suggestions in this spirit (de Bruijn 2001). He suggested naming the finer local/regional biostratigraphic zonations according to region (MNSP for Spain, MNCE for Central Europe etc.). In addition, he proposed to keep the name MN for the low-resolution, continent-wide system of reference faunas.

There are two possibilities for the representation of the reference localities which will be discussed below: either as discrete points on a scale or as boundaries of faunal units.

Spanish Neogene mammal zonation

Currently, the Spanish Neogene mammal record is the only European mammal record sufficiently complete and dense to allow a series of formal biozone boundaries to be defined with reasonable chronological precision. The system of biozones defined on the basis of the exceptionally dense small-mammal record from the Calatayud-Daroca and Teruel Basins (Daams & Freudenthal 1981, Daams & van der Meulen 1984, Daams *et al*. 1998, Mein *et al*. 1990, van Dam *et al*. 2001) could form the backbone for such a standard zonation. Additional information from other Spanish basins could easily be fit in.

Mammal Neogene locality scale

The current system of European reference faunas (de Bruijn *et al*. 1992), or its alternative form with localities as boundaries (see below), should explicitly be linked to the local but well-dated Spanish mammal zonation, resulting in a tool for long-distance correlations. Maximal effort should be made to ensure the best possible correlations of the European reference localities to the Spanish small mammal scale. It is a matter of discussion whether the name ‘MN’ should be maintained for the ‘European part’ of the system because of possible misunderstandings regarding its contents (Fig. 1). In order to avoid any further confusion a designation such as ‘Mammal Neogene Locality Scale’ could be used.

Mammal Neogene localities as boundaries

In this alternative representation, which is a continuous equivalent of the discrete locality scale above, boundaries of faunal units are unequivocally defined in the reference localities themselves. Faunal intervals could be called after their boundaries (e.g. Can Llobateres- Masía del Barbo interval fauna), in order to avoid confusion with the numbered reference localities of the locality scale above. The role of the larger continental units (Stages/Ages, Megazones) in such a combined system is unclear. In my opinion, the use of marine Stage/Age names should be (re)-considered by continental workers, given the recent increase in the number of marine-continental correlations. In addition, a common language will facilitate the communication with colleagues working in the marine realm.

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