



Chronology of the late Turolian deposits of the Fortuna basin (SE Spain): implications for the Messinian evolution of the eastern Betics

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Received 30 March 1998; revised version received 7 July 1998; accepted 11 August 1998

Abstract

The magnetostratigraphy of the mammal-bearing alluvial fan–fan delta sequences of the Fortuna basin (SE Spain) has yielded an accurate chronology for the late Turolian (Messinian) basin infill. From early to late Messinian (at least between 6.8 and 5.7 Ma), the Fortuna basin records the sedimentation of alluvial–palustrine deposits over a confined shallow basin. Changing environmental conditions in the latest Messinian are illustrated by the retreat of palustrine facies. A rapid progradation of the marginal clastic wedges and the initiation of an efficient basin drainage at ~5.8 Ma (lower part of chron C3r) most likely represents the onshore response to the drastic drop of base level taking place during the Messinian salinity crisis. This study further provides improved age estimates for the late Turolian land mammal events in southern Spain. The oldest MN 13 locality in the studied sections is correlated to chron C3Ar at an age of 6.8 Ma. The entry of camels and the murid *Paraethomys* in southern Spain occurs in chron C3An.1n at 6.1 Ma, and gives further support for land mammal exchange between Africa and the Iberian peninsula prior to the salinity crisis, in good agreement with results from northern Africa [M. Benammi, M. Calvo, M. Prévot, J.J. Jaeger, Magnetostratigraphy and paleontology of Aït Kandoula basin (High Atlas, Morocco) and the African–European late Miocene terrestrial fauna exchanges, *Earth Planet. Sci. Lett.* 145 (1996) 15–29]. The age of the studied sequences provides important constraints on the understanding of the sedimentary evolution of the eastern Betic margin, and shows that previous interpretations of the evaporitic–diatomitic sequences of the Fortuna basin, as being coeval to the late Messinian salinity crisis in the Mediterranean, are not correct. The confinement leading to the emergence of the Fortuna basin occurred in the late Tortonian to earliest Messinian, similar to other intramontane basins in the Betics. Therefore, the inclusion of the Fortuna basin in a hypothetical marine Betic Corridor during the late Messinian is no longer tenable. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Spain; Betic Zone; Messinian; Turolian; magnetostratigraphy; biostratigraphy; mammals

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1. Introduction

The Neogene basins in the eastern Betic Ranges (SE Spain) offer a privileged setting to study the evolution of the western Mediterranean basin during the late Miocene and Pliocene [1–3]. Two marine gateways connected the western Mediterranean to the Atlantic in late Tortonian times, the Rifian Corridor through Morocco and the North Betic Corridor through Spain. Ongoing tectonic processes, and a superimposed paleoclimatic (glacio-eustatic sea-level fluctuations) component, progressively closed these gateways during the Messinian and caused a complete isolation of the Mediterranean. The result was a series of successive events that changed the paleogeography and paleoceanography of the Mediterranean. The best known, but least understood, event is the ‘Messinian salinity crisis’, a period during which very thick evaporite units were deposited all over the Mediterranean, followed by continental and brackish water sediments which are related to the desiccation phase of the latest Messinian. Paleogeographic reconstructions of these marine gateways, as well as the precise age of closure, are still uncertain because tectonic deformation and large-scale olistolith bodies, covering the youngest marine sediments, hamper a reliable age control.

Paleogeographic reconstructions of the eastern Betics [3] indicates that the Fortuna basin (Fig. 1) occupied the northeastern part of the Betic Corridor. The sedimentary infill of the Fortuna basin [1,4–6] can be grouped into three main units: (1) a thick marine sequence consisting of turbidites and pelagic marls (Los Baños Formation [4]), informally referred to as Fortuna marls [1], (2) a regressive evaporitic sequence [7] with gypsiferous marls, diatomites, massive gypsum and conglomerates (Rio Chicamo Formation [4]), and (3) a post-evaporitic basin infill consisting of a mainly continental alluvial to lacustrine succession (Rambla Salada Formation [4]). The regressive sequence from marine marls to evaporites and continental deposits has been interpreted in the context of sea level lowering that led to the Messinian salinity crisis [6]. Furthermore, detailed correlations were proposed between the Rio Chicamo evaporites and the well-known gypsum deposits (Lower Evaporites) of the Mediterranean basin [4,8]. Based on these correlations, Müller and Hsü

[4] claimed that the marine connection through the Betic corridor was open till the latest Messinian.

These correlations and interpretations were not substantiated, however, by a better resolved chronology. Concerning the age of the formations there have been conflicting interpretations. While early datings suggested a latest Tortonian age for the evaporites of the Fortuna basin [1], a revised planktonic biostratigraphy led Lukowski and colleagues [9] to date the Fortuna marls as Messinian. Consequently, the overlying evaporites were considered as late Messinian. However, the postulated Messinian age for the Fortuna marls is not validated by any convincing biostratigraphic marker. The FAD of *Globorotalia conomiozea* denotes the lower boundary of the Messinian Stage, but this species is not found in the pre-evaporitic planktonic-rich facies of the central part of the basin [9,10], while it is cited in the shallow deposits overlying the onset of the evaporites and confined conditions [1,5].

In contrast to the marine units, the continental sequences of the Fortuna basin provide a reliable and detailed biostratigraphic record. Several rich, late Turolian, vertebrate assemblages [11–14] indicate a middle to late Messinian age for these sediments. This age is supported by marine–continental correlations of classical localities in neighbouring regions [15,16]. In this paper we present the magnetostratigraphy of the late Turolian alluvial fan–fan delta sequences which crop out along the SE margin of the Fortuna basin. The results of this study provide an accurate chronology for the late Turolian (Messinian) bioevents in the western Mediterranean, as well as important constraints on the sedimentary evolution of the east Betic margin.

2. Geological setting of the Fortuna basin

The pre-Neogene rocks of the eastern Betics are divided into two units (Fig. 1). The External Betics consist of the deformed southeastern margin of the Iberian Massif and the Internal Betics consist of the allochthonous units which were incorporated into the orogen after a westward drift during the middle Miocene. A number of intramontane basins developed in the eastern Betics since the early Tortonian [3,17,18] under an overall NNW–SSE compressional

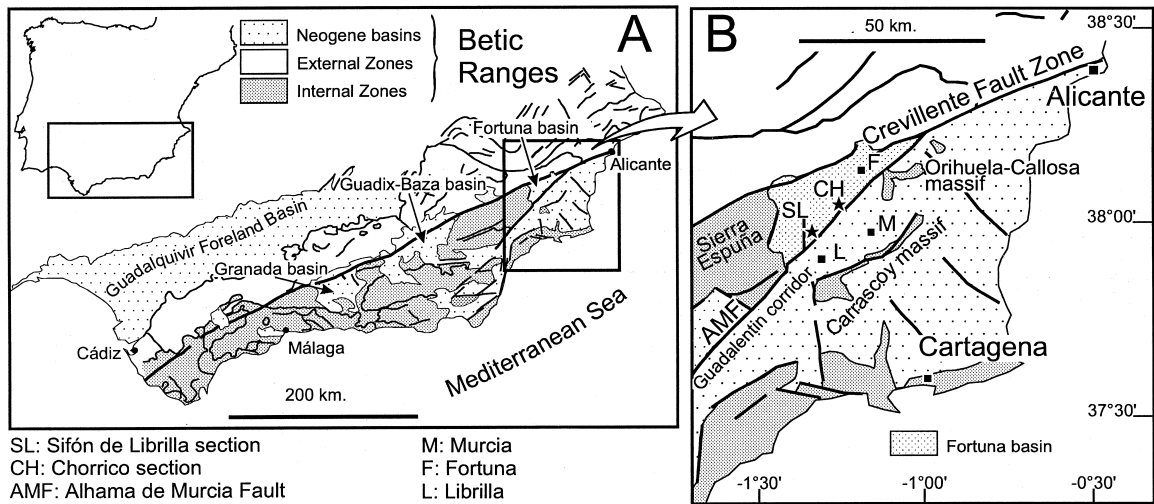


Fig. 1. (A) Geological sketch of the Neogene basins in the Betic Ranges. The Granada, Guadix–Baza and Fortuna basins, lying on the contact between the External and Internal Zones, formed part of a North Betic corridor [3] which connected the Atlantic and the Mediterranean in late Tortonian times. (B) The Fortuna basin in the eastern Betics is bounded by two major shear zones, the Crevillente and the Alhama de Murcia faults. The Carrascoy and Orihuela–Callosa massifs are relicts of its south-eastern margin. *SL*: Sifón de Librilla section; *CH*: Chorríco section; *AMF*: Alhama de Murcia Fault; *M*: Murcia; *F*: Fortuna; *L*: Librilla.

regime [3,19] as a result of the Africa–Europe plate collision.

The Fortuna basin (Fig. 1) lies on the contact between the External and Internal Betics and is bounded by two major NE–SW shear zones. The North Betic–Crevillente fault zone [20] delineates the tectonically active northwestern basin margin, which acted as the main sediment source. The Alhama de Murcia wrench fault [21,22] lies along the Guadalestín corridor and approximately outlines the SE margin of the Fortuna basin. Late Neogene N–S compression resulted in important left-lateral shear and basement uplift along the basin margins. An emerged massif to the East of the Alhama de Murcia Fault [1,21] acted as an active source area for a set of alluvial fans which spread into the basin during the late Miocene. Relics of this paleorelief are the Carrascoy, Orihuela and Callosa massifs (Fig. 1), which mainly consist of Permian–Triassic metasediments and volcanic rocks of the Internal Betics. The tectonic uplift of the southeastern margin played an important role in the initiation of restricted environments and the subsequent isolation of the Fortuna basin from the Mediterranean basin [5].

3. Studied sections

The present study focuses on the sediments spanning the lower part of the post-evaporitic continental unit. Best suited outcrops of these sediments lie close to the southeastern margin of the Fortuna basin, where folding and tilting propitiate the exposure of thick sediment successions. Two sections (Chorríco and Sifón de Librilla) with numerous vertebrate fossil traces were selected while taking into account the need of a precise biochronologic constraint for this study.

The Chorríco (CH) section is situated in the Molina de Segura suburbs, 6 km to the north of Murcia (Fig. 1), where beds dip 50° towards the northwest. The base of the section directly overlies the gypsiferous unit by means of a lateral-slip fault contact. The CH section is about 350 m thick and can be divided into two interfingering facies assemblage units (Fig. 2). The main unit consists of alternating gypsiferous marls, silts, and conglomeratic sandstones arranged in a prograding alluvial fan–fan delta sequence. Mesozoic and Tertiary limestones from the External Betics (western Fortuna margin) are the main source rocks for these sediments. Pa-

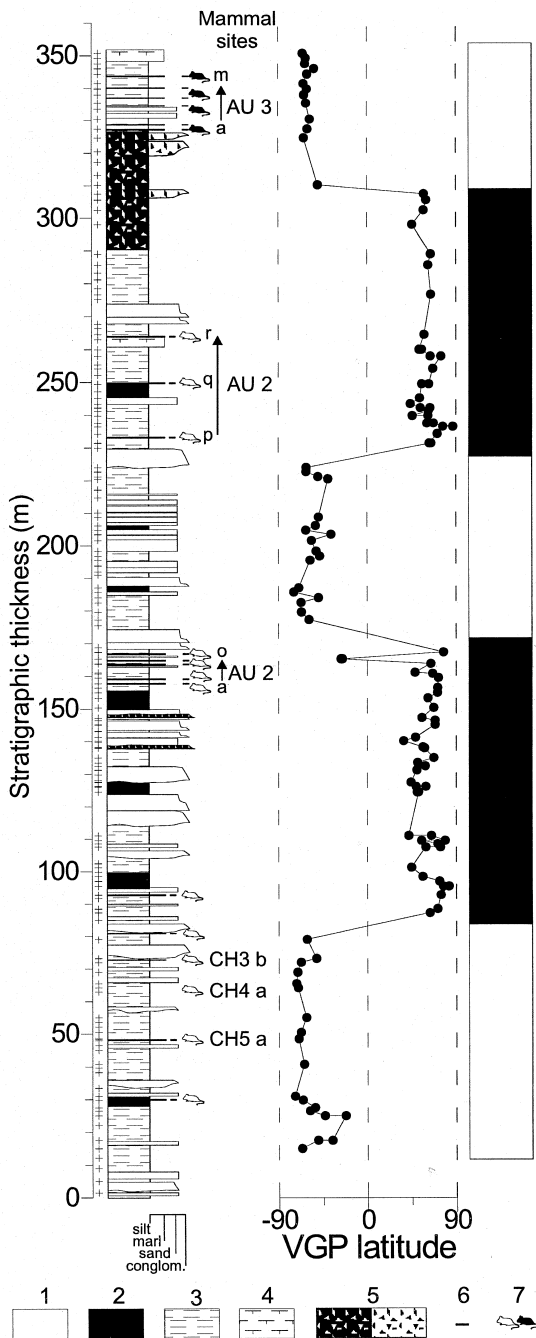


Fig. 2. The Chorrigo magnetostratigraphy. Legend: 1: sandstones and conglomerates; 2: red silts; 3: light coloured silts; 4: grey marls; 5: Red clays and breccias ('Conglomerates of Murcia' unit); 6: dark organic-rich silts; 8: mammal sites (in black *Paraethomys* bearing sites).

leolosols or other evidences of subaerial exposure are not observed, but the abundance of levels with small mammal fossils suggests a dominantly emergent or very shallow transitional deltaic environment [6]. In the studied section marine fossils, other than reworked planktonics from the underlying Tortonian marls, are unknown. However, marine influxes in the lowermost part cannot be totally excluded because marine fossils are reported from laterally equivalent (towards the NE) sediments [5].

In the upper part of the CH section, a second facies assemblage interfingers with the main unit. It consists of alluvial red clays and massive monogenic breccias. Their immature sedimentary fabric denotes the predominance of mass-flow processes and a relatively short transport from the source area. In contrast to the CH main unit, the source rocks of these sediments are Permotriassic phyllites and quartzites corresponding to the Internal Betics, which crop out in the massifs to the east of the Alhama de Murcia Fault. This unit is referred to part of the so called 'Conglomerates of Murcia' [1], a marginal alluvial unit associated with the erosion of the paleomassif that extended to the east of the Alhama de Murcia Fault since the late Tortonian.

The Sifón de Librilla (SL) section [18] is exposed along the eastern flank of a syncline structure to the north of Librilla (Fig. 1). The sampled succession shows a gentle dip (25 to 30°) towards the west. The section consists of 360 m of alluvial red beds, where red silts alternate with palustrine grey marls and minor channelled conglomerates and sandstones (Fig. 3). The fine-grained facies in the upper part of the section shows a distinct alternation of alluvial red silts and palustrine grey marls. Transition from alluvial to palustrine facies occurs through red-and-grey mottled facies showing traces of hydromorphous paleosols. The top of the grey marl intervals contains organic-rich reduced facies, with abundant gastropod shells and small mammal fossil remains. Very thin laminated lacustrine limestones also occur associated to the palustrine facies.

The SL section records a change in the sedimentary conditions towards the top of the sequence. It is marked by the retreat of the grey reduced facies, providing evidence for a drastic decline of ponded areas and the enhancement of the basin drainage. Hydromorphous paleosols disappear and red allu-

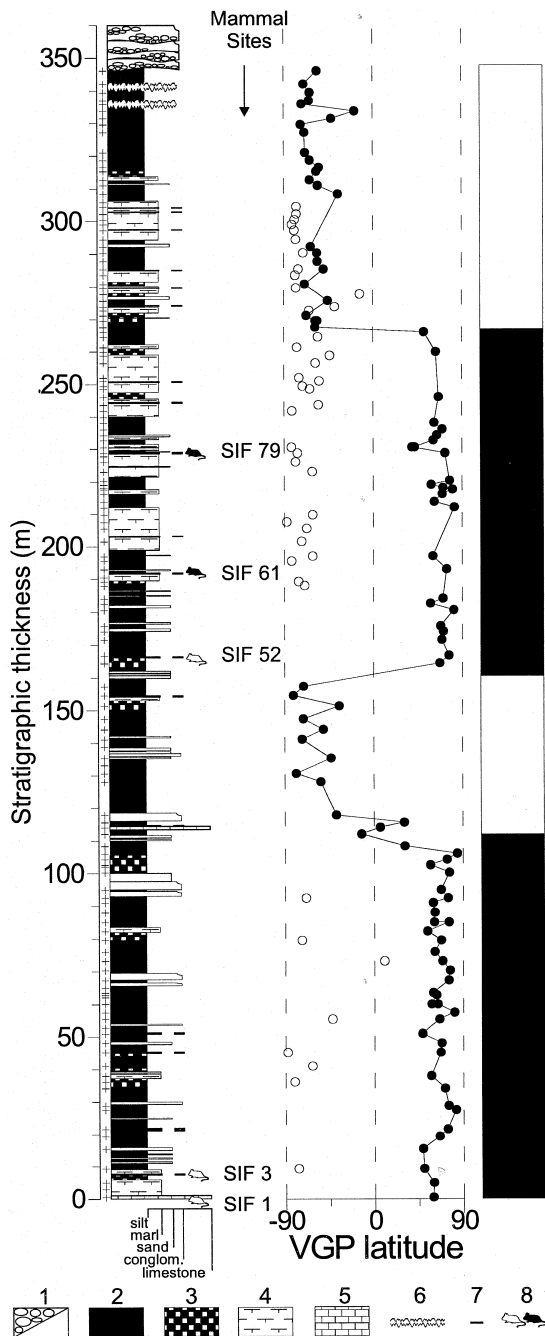


Fig. 3. The Sifón de Librilla magnetostratigraphy. Closed circles represent component A (primary) paleomagnetic directions, open circles represent (secondary) component B directions. Legend: 1: sandstones and conglomerates; 2: red silts; 3: mottled silts (hydromorphous paleosols); 4: grey marls; 5: limestones; 6: carbonate crusts (caliche paleosols); 7: dark organic-rich silts; 8: mammal sites (black portrays *Paraethomys* bearing sites).

cial sedimentation alternates with carbonate crusts (caliche paleosols). The top of the section is formed by a succession of thickly bedded conglomerates. The conglomerate clasts mainly consist of Mesozoic and Tertiary limestones, indicating a main terrigenous sediment supply from the External Betics (western basin margin).

4. Mammal biostratigraphy

The Turolian continental stage [23] comprises the European Mammal Neogene (MN) reference assemblages MN11 to MN13 [24,25]. In the eastern Betics, a number of studies have contributed to construct a high-resolution biostratigraphy for this time slice [1,12–15]. Datable volcanic rocks, interbedded within the sediments [5,11] and the lateral interfingering between marine and continental units have provided the mammal biozonation with some useful constraints on absolute ages. In this region, the late Turolian (MN13) faunas broadly correlate to the Messinian [15,16]. Also, in the Cabriel Valley (Valencia, east Spain), the MN12/MN13 boundary has been approximately dated to 6.7 Ma (lower Messinian) by means of magnetostratigraphy [26]. The MN13/MN14 (Turolian/Ruscinian) boundary, traditionally positioned at the Messinian/Zanclean boundary, is correlated in the Cabriel section to the interval between chrons C3n.3n and C3n.4n (lower Pliocene), with an age of 4.9 Ma [26].

The late Turolian mammal fauna in the Iberian peninsula is characterised by the entry of a significant number of immigrants of African and Asiatic affinities ([13]). Among rodents, *Stephanomys* and *Apodemus* are the most characteristic late Turolian murids in the western European basins [27–29]. An especially relevant bioevent is the entry of *Paraethomys miocaenicus*, an Asiatic immigrant which colonised both shores of the Mediterranean basin [28–31]. The best-documented late Turolian localities of southern Spain, containing *Paraethomys miocaenicus*, are the classic sites of Librilla [11,15,32,33], Crevillente 6 [15] and La Alberca [11,16]. The close similarities to the lower Ruscinian (MN14) site of Alcoy (Alicante) suggest that the fauna of La Alberca (at the northern slopes of the Carrascoy massif, NE of Librilla) is

slightly younger than Crevillente 6 and Librilla, and biochronologically close to the Turolian/Ruscinian boundary [16]. The stratigraphic position of both La Alberca and Crevillente 6, interbedded within a marine sequence with *G. conomiozea* [15,16], provides assignment of Messinian Stage to these sites.

The biostratigraphic data of this study constrain the stratigraphic datum for the entry of *Paraethomys*. In the CH section (Fig. 2) sites CH5a, CH4a, CH3b, and AU2a to AU2r yielded a characteristic late Turolian assemblage with *Stephanomys ramblensis*, *Occitanomys adroveri*, *Apodemus gudrunae*, *Ruscinomys lasallei* and *Cricetus kormosi*. At sites AU3, *Paraethomys miocaenicus* occurs, together with *Stephanomys ramblensis*, *Cricetus kormosi* and *Ruscinomys lasallei*.

In the SL section (Fig. 3), sites SIF-1, SIF-3, and SIF-52 yield an assemblage with *Apodemus aff. gudrunae* and *Stephanomys ramblensis* [14]. Occurrence of *Paraethomys miocaenicus* is found at sites SIF-61 and SIF-79. The classic *Paraethomys*-bearing site referred in the literature to as Librilla [11,14] can be correlated to a level between SIF-61 and SIF-79. In the same stratigraphic position, the occurrence of camels assigned to the genus *Paracamelus* was reported, which is the oldest record of this eastern immigrant taxon in the Old World [32,33], together with the site of Venta del Moro in Valencia [34].

The entry of eastern immigrants such as *Paracamelus aguirrei* in southern Spain during the late Miocene is suggested to proceed via North Africa [35] since this species is unknown in the rest of

the European Turolian large mammal sites. Among rodents, the entry of *Paraethomys* may represent the same dispersal event since the first appearance of this species occurs in Librilla at the same stratigraphic position as *Paracamelus*. Further evidences of a late Turolian intercontinental faunal exchange are the occurrences of some rodent genera of western European origin such as *Apodemus*, *Prolagus*, *Occitanomys* and *Cricetus* in the Ait Kandoula Basin (High Atlas, Morocco) [36]. This implies an ephemeral land bridge between north Africa and western Europe prior to the late Messinian isolation of the Mediterranean basin [37].

5. Paleomagnetic analysis

The paleomagnetic study of the SL and CH sections is based on the analysis of 300 magnetostratigraphic sites, cored in the field with a portable drill. The natural remanent magnetisation (NRM) was studied in the laboratory by means of standard stepwise thermal (TH) demagnetisation procedures. Additional IRM experiments were carried out to check for differences on the ferromagnetic composition among lithologies and to identify the remanence carriers.

5.1. The Chorrico (CH) section

Thermal demagnetisation of samples from the CH section reveals a two-component NRM (Fig. 4).

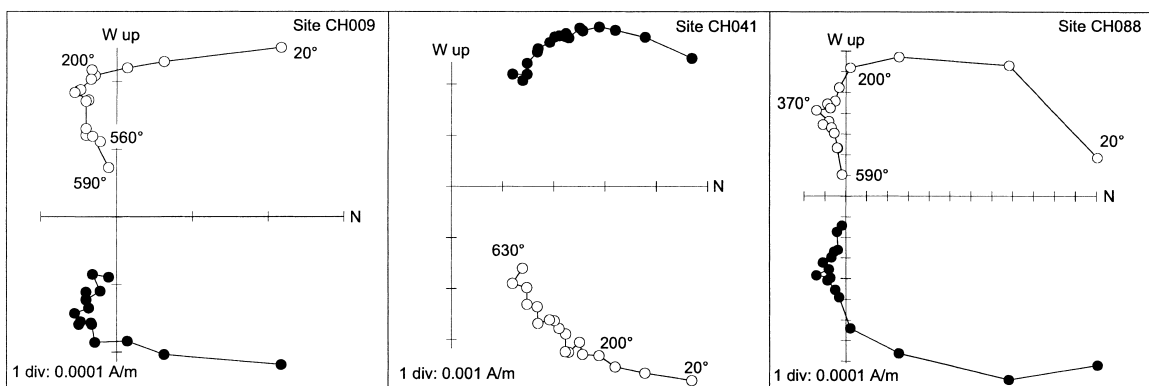


Fig. 4. NRM demagnetization diagrams of representative samples from the Chorrico section. All the projections in tectonic corrected coordinates.

Table 1
Mean directions and Fisher statistics of the Chorrico and Sifón de Librilla sections

Sites		N	Geographic coordinates				Bedding coordinates			
			dec	inc	k	α_{95}	dec	inc	k	α_{95}
Chorrico										
	Normal	68	278	40	12	5	326	30	12	5
	Reversed	52	96	-23	10	6	120	-22	11	6
Sifón de Librilla										
component A	Normal	59	26	67	19	4	349	41	17	5
	Reversed	36	221	-59	8	9	189	-37	8	9
component B	Reversed	44	219	-70	10	7	175	-47	12	7

The low temperature (up to 300°C) component in geographic coordinates yields an average direction which approximately conforms to the present day field dipole. A characteristic remanent magnetisation (ChRM) is isolated above 300°C and shows both normal and reversed polarities. Thermal decay of the ChRM frequently shows steep intensity decreases below 590°C, but higher temperatures (up to 680°C) are required for complete demagnetisation of most of the samples. This suggests that NRM is carried by iron oxides such as hematite and magnetite. Normal and reversed ChRM directions do not show perfect antipodal directions (angle between normal and reverse polarity sets equals to 17°), and fail to pass the reversal test [38], suggesting an incomplete cleaning of secondary components. The overall mean direction (reverse samples rotated to antipodal) yields 309/27 after correction for bedding tilt, thus report-

ing an apparent vertical axis rotation of as much as 50° (Table 1, Fig. 5). The paleomagnetic data indicates a very substantial anticlockwise rotation in this sector, which can be linked to the prevalent left-lateral shear associated to the Alhama de Murcia wrench fault [22,39].

5.2. The Sifón de Librilla (SL) section

Thermal demagnetisation of samples from the SL section frequently yields two paleomagnetic components after removal of the secondary low temperature magnetisation (Fig. 6). The unblocking temperature spectra of these two components do not overlap significantly and their directions can be properly calculated by means of least-square analysis of the demagnetisation data [40].

The highest temperature component (component

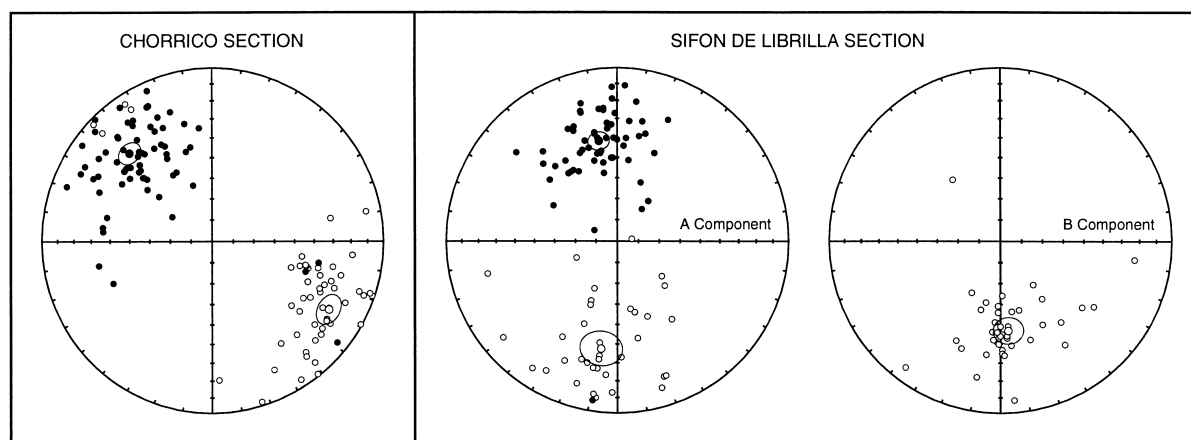
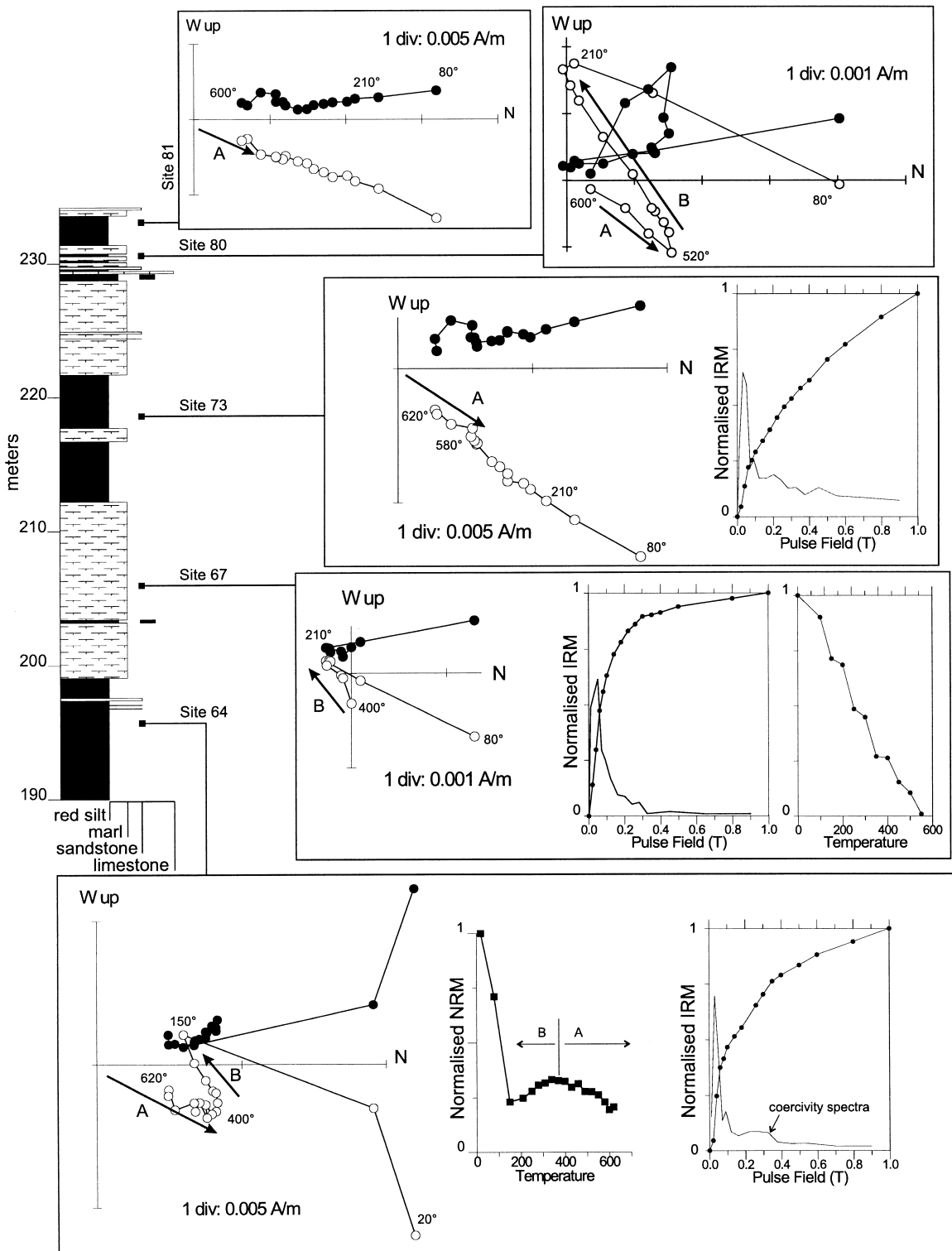


Fig. 5. Stereonet projection of paleomagnetic directions from the CH and SL sections after correction for bedding tilt. See Fisher statistics in Table 1.



A) is invariably present in samples of red and mottled silts (Fig. 6). Its maximum unblocking temperatures are well above 660°C and this reveals the presence of hematite as the main remanence carrier. Component A yields both normal and reverse polarities (Fig. 5), recording a sequence of four stratigraphic polarity zones (Fig. 3). Mean directions in geographic coordinates yield reliable inclinations but declinations are rotated clockwise. After correction for bedding tilt, mean directions conform to a northerly (unrotated) shallow magnetisation (Table 1).

In addition to component A, an intermediate temperature paleomagnetic magnetisation (component B) is defined in the range 250–500°C. It is regularly present in all samples from the grey marl intervals, but also in many red-grey mottled samples and in some red silts close to the greyish facies. Component B always yields reverse polarity (Fig. 5). The mean direction in geographic coordinates averages 219/–70, and 175/–47 after bedding correction, thus supporting an early pre-tilt magnetisation (Fig. 5). Both NRM unblocking temperatures and coercivity spectra from IRM acquisition curves suggest the presence of magnetite as the principal magnetic phase in the grey sediments, and the most likely carrier of the component B (Fig. 6).

The fact that component A records a consistent sequence of polarity reversals (Fig. 3) supports an early (primary) magnetisation. In contrast to the results from the CH section, the mean paleomagnetic direction in the SL section does not support vertical axis rotations in this sector. Magnetisation of component A in the SL section was likely affected by appreciable inclination shallowing upon deposition and/or subsequent compaction, similar to the CH section.

We must conclude that component B represents an early (pre-tilt), but secondary magnetisation, which selectively affected the organic-rich greyish facies. The fact that component B is tightly clustered to a reversed paleomagnetic direction suggests that the

demagnetisation is associated to a single discrete (short-lived) event, rather than to a process operating continuously through diagenesis. This particular event must have taken place within a period of reverse geomagnetic field.

6. Magnetostratigraphic correlation and biochronological implications

The virtual geomagnetic pole (VGP) latitudes of the characteristic paleomagnetic directions yield a well defined magnetic polarity sequence in both the CH and SL sections (Figs. 2 and 3). In the CH VGP latitudes were calculated after correcting the paleomagnetic declinations for the observed vertical axis rotation discussed above. The appearance of *Paraethomys* in both sections allows an unequivocal correlation between the two magnetic polarity sequences (Fig. 7). Given the additional constraint that the mammal assemblages found in the sections are of Messinian age [15,16], a unique correlation with the geomagnetic polarity time scale is feasible (Fig. 7). The resulting absolute chronology implies that the composite sequence of the continental Rambla Salada Formation in the Fortuna basin represents more than 1 My, covering the early to latest Messinian, from approximately 6.8 to 5.7 Ma. The entry of the eastern immigrants *Paracamelus aguirrei* and *Paraethomys miocaenicus* is accurately dated in the lower part of chron C3An.1n at an age of approximately 6.1 Ma.

Our correlation is in good agreement with the data from the Cabriel basin (eastern Spain), where the late Turolian fauna of Venta del Moro is correlated to lower chron C3r [26]. In this concern, the age of Venta del Moro is of special value because its fauna also includes *Paraethomys miocaenicus* and *Paracamelus aguirrei* and shares most of the other elements with the *Paraethomys*-bearing localities of our sections. The entry of eastern immigrants in

Fig. 6. NRM demagnetization diagrams of samples from a particular stratigraphic interval in the Sifón de Librilla section with cyclic alternations of red alluvial silts and palustrine/lacustrine grey marls. A high temperature component (A) is present in all the red samples. In some of these, an intermediate temperature component (B) is also recognised (sites 64 and 80). Component B is prevailing in the grey intervals (site 67), where component A may be absent. Component B always yields reverse polarity, while component A records up to three polarity transitions (see Fig. 3). All the projections in tectonic corrected coordinates.

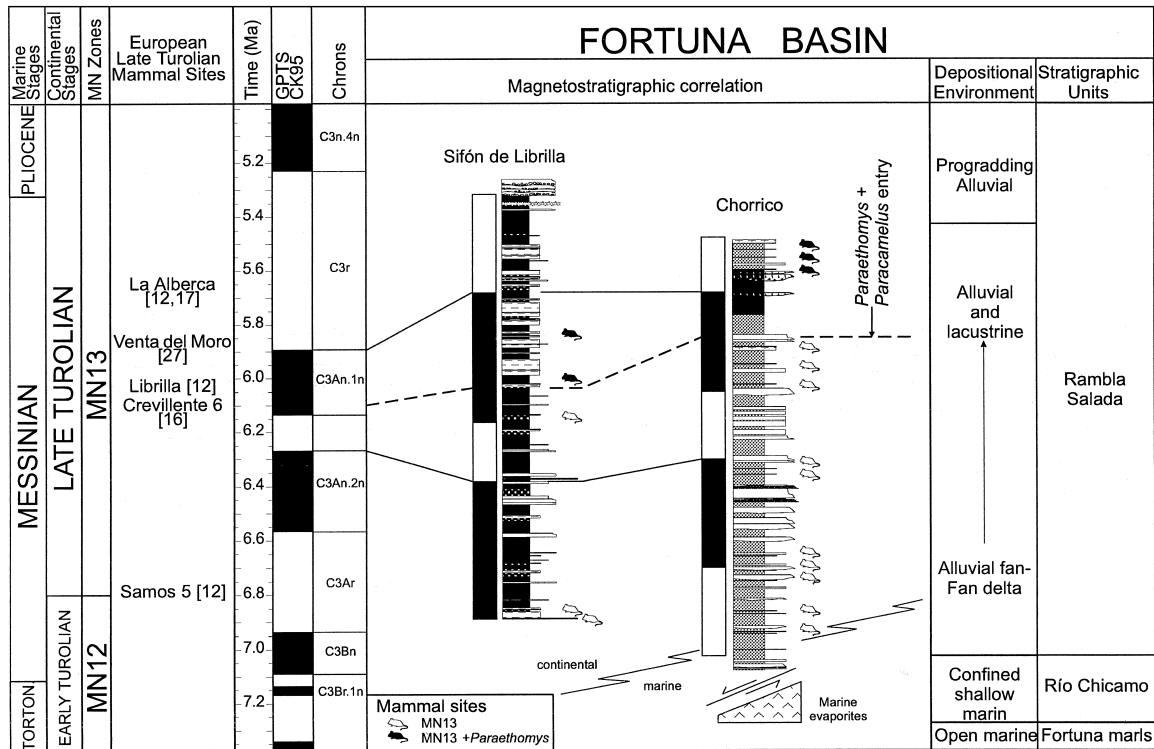


Fig. 7. Correlation of the Messinian alluvial and lacustrine sequences in the Fortuna basin with the geomagnetic polarity time scale and the marine and continental chronologies. The age of Samos 5 [11], Librilla (this study) and Venta del Moro [26] are based on magnetostratigraphy. The age of Crevillente 6 and La Alberca are based on marine–continental correlations.

Spain is in full coincidence with the reported age for the arrival of European immigrants into northern Africa [37]. This further supports a late Messinian intercontinental mammal exchange starting at least as early as 6.1 Ma, well before the main evaporitic phase of the Mediterranean salinity crisis which is magnetostratigraphically dated at 5.8 Ma [41].

Earlier magnetostratigraphic datings in the Cabriel valley [26] yielded an approximate age for the not well-constrained MN12/MN13 boundary of 6.7 Ma, below the base of C3An. In the CH section, the earliest late Turolian (MN13) mammal site occurs somewhat older in chron C3Ar, at approximately 6.8 Ma. Thus, from this study, an age for the MN12/MN13 boundary older than 6.8 Ma is preferred. This contradicts earlier correlations of the MN12 reference mammal site of the Casa del Acero to the late Messinian, which were inferred from its stratigraphic location within the evaporitic sequences in the Fortuna basin [12]. However, as

discussed below, the supposed late Messinian age of the evaporites in the Fortuna basin is untenable and, in consequence, the precise age of Casa del Acero is unresolved.

Our ages are congruent with the magnetostratigraphy of Samos (Greece) where basal MN 13 fauna is correlated to chron C3Ar [42], and with the recently reported $^{40}\text{Ar}/^{39}\text{Ar}$ datings of mammal faunas from eastern Mediterranean and Iran [43] suggesting a correlation of the base of MN13 to the base of the Messinian stage [44].

7. Chronology of the Fortuna basin and consequences for the Messinian evolution of the western Mediterranean

The magnetostratigraphic dating of the post-evaporitic alluvial sequences provides new clues for the chronology of the basin infill. In the CH section,

sediments record the emergence of a confined shallow basin during the early Messinian (older than 6.8 Ma). The overall sequence represents a progradation of the conglomeratic alluvial fans fed from the northwestern basin margin. These interfinger with the Conglomerates of Murcia, which consist of smaller scale alluvial fans fed from the opposing southeastern margin. In the SL section we observe that alluvial and palustrine sedimentation alternated for almost 1 My, from middle to late Messinian (at least between 6.5 and 5.8 Ma). The frequency of reducing palustrine facies indicates an inefficient basin drainage, which prompted the development of ephemeral ponded areas. The scenario changes at the top of the section, where palustrine deposits disappear and an overall progradation of the alluvial system takes place. Hydromorphous paleosols are replaced by caliche crusts, suggesting a drier and better drained environment. This change occurs in the lower part of chron C3r at approximately 5.8 Ma, and is most likely coeval to the decrease of the base level associated with the beginning of the Messinian salinity crisis.

We conclude that basin confinement and the following precipitation of evaporites in the Fortuna basin has taken place earlier, during the latest Tortonian to the earliest Messinian, indicating that these evaporites are not coeval with, but predated the evaporites of the Mediterranean salinity crisis. Therefore, the inclusion of the Fortuna basin in a hypothetical Betic marine corridor during the late Messinian [4] is untenable. The primary role of the eustatism in the Fortuna basin evolution [6] was criticised earlier [5] because it ignored the tectonic deformation that took place during the deposition of the Miocene sequences in the Fortuna basin. Lukowski [5] stressed the importance of the tectonic uplift of the basin margins as the cause for the isolation of the basin and the precipitation of the evaporites. The early initiation of confinement leading to marine regression and terrestrial environments is not restricted to the Fortuna basin. Other intramontane basins, lying on the contact between the External and Internal Betics, show a comparable evolution. The age of the emergence of the Granada [45,46] and Guadix–Baza basins [47] which resulted from the orogenic uplift coupled with a period of eustatic downfall, is correlated to late Tortonian–early Messinian.

8. Remagnetisation in the Sifón de Librilla section

In the SL section, remagnetisation typically occurs in the grey intervals (component B in Fig. 3). Although a detailed analysis of its origin is beyond the scope of this paper, this subject deserves a detailed separate study because it is of fundamental interest and has important implications for the acquisition of the NRM in this type of (palustrine–alluvial) sediments.

From what we have observed the remagnetisation is likely related to a discrete event during a period of reversed polarity which caused an intermediate temperature reversed component to originate in all grey beds of the section. The remagnetisation must have taken place in an early stage because of its pre-folding age. A likely period for this event is the upper reverse magnetozone in the Librilla section, where we find the change from a palustrine–alluvial to a prograding alluvial system, which is suggested linked to the base level drop of the Mediterranean late Messinian. A possible cause for the remagnetisation component is that this base level drop caused an increased and efficient drainage of groundwater, thus exposing a reduced environment (the grey layers) to oxidation. Oxidation of iron sulphides to magnetite would cause a newly formed chemical remanent magnetisation, acquiring the then ambient (reversed) field. The suggested driving mechanism for fluid migration in the SL section, would be a eustatic base level lowering, in contrast to other reported ancient remagnetisations where fluid migration is induced by tectonic stress [48].

9. Conclusions

In the Fortuna basin, the Messinian Stage is mainly represented by continental alluvial-fan to fan-delta and lacustrine sediments of the Rambla Salada Formation, overlying the shallow marine diatomitic–evaporitic sequences usually referred to the Chicamo Formation [4]. The initiation of the terrestrial environments in the Fortuna basin correlates to a latest Tortonian–earliest Messinian event, similar to other intramontane basins of the central Betics.

The oldest fossil mammal locality in the studied

sections is attributed to MN 13 and is correlated to chron C3Ar at an age of 6.75 Ma. Thus, from this study an age for the MN12/MN13 boundary older than 6.8 Ma is preferred. The emergence of the Betics intramontane basins is followed by the first terrestrial faunal exchange between Africa and Europe at 6.1 Ma, when western European rodents arrive in northern Africa [37,36] and genera of Asiatic affinities appear in the Fortuna Basin (this study). Consequently, the tectonic uplift leading to the emergence of the central and eastern Betic basins also disrupted the seaway between the Mediterranean and the Atlantic, prompting intercontinental land-mammal exchange.

The proposed chronology revises previous models, in which the evaporitic phases in the Fortuna basin were correlated to the Messinian salinity crisis, and in which eustatic sea-level change was suggested the primary controlling factor in the progressive isolation of this marginal basin from the open sea [4,6,8]. Also, the inclusion of the Fortuna basin in a hypothetical Betic marine corridor during the late Messinian [4] is no longer tenable.

Acknowledgements

Supported by the Netherlands Geosciences Foundation (GOA) with financial aid from the Netherlands Organisation of Scientific Research (NWO), the Spanish Ministry of Education and Science PB94-1265 project, the Comissionat per Universitats i Recerca de la Generalitat de Catalunya Grup de Qualitat GRQ94-104, and EC Project CII-CT94-0114. We thank M. Freudenthal, E. Martín-Suárez, M. Llenas and M. Guitart for their collaboration in the biostratigraphic samplings. We also thank C. Langereis, M. Woodburne and E. Lindsay for reviewing the manuscript. [RV]

References

- [1] C. Montenat, Les formations néogènes et quaternaires du Levant espagnol (Provinces d'Alicante et de Murcia), Ph.D. Thesis, Université d'Orsay, 1973, 1170 pp.
- [2] C. Montenat, Le Miocene terminal des chaines betiques (Espagne meridionale). Esquisse paleogeographique, Proc. Kon. Ned. Akad. Wetensch. 180–187, 1973.
- [3] C. Sanz de Galdeano, J.A. Vera, Stratigraphic record and palaeogeographical context of the Neogene basins in the Betic Cordillera, Spain, *Basin Res.* 4 (1992) 21–36.
- [4] D.W. Müller, K.J. Hsü, Event stratigraphy and paleoceanography in the Fortuna basin (Southeast Spain): A scenario for the Messinian salinity crisis, *Paleoceanography* 2 (1987) 679–696.
- [5] P. Lukowski, Evolution tectonosédimentaire du bassin Neogene de Fortuna (Cordillères bétiques orientales, Espagne), Ph.D. Thesis, Université de Paris Sud, 1987, 403 pp.
- [6] C. Santisteban, Petrología y sedimentología de los materiales del Mioceno superior de la cuenca de Fortuna (Murcia), a la luz de la 'teoría de la crisis de salinidad', Universitat de Barcelona, 1981, 722 pp.
- [7] F. Ortí, J. García-Veigas, L. Rosell, J.M. Rouchy, M. Inglès, D. Gimeno, A. Kasprzyk, E. Playà, Correlación litoestratigráfica de las evaporitas messinienses en las cuencas de Lorca y Fortuna (Murcia), *Geogaceta* 14 (1993) 98–101.
- [8] D.W. Müller, H. Schrader, Diatoms of the Fortuna basin, Southeast Spain: evidence for the intra-Messinian inundation, *Paleoceanography* 4 (1989) 75–86.
- [9] P. Lukowski, R. Wernli, A. Poisson, Mise en évidence de l'importance des dépôts messiniens dans le bassin Miocene de Fortuna (Province de Murcia, Espagne), *C.R. Acad. Sci. Paris* 307 (1988) 941–947.
- [10] F.J. Sierro, J.A. Flores, J. Civis, I. Zamarreño, A. Vázquez, C. Santisteban, J. Porta, Las margas de Fortuna: Bioestratigrafía y caracterización paleoceanográfica, III Congr. Geol. España, 1992, pp. 222–226.
- [11] C. Montenat, L. Thaler, J.A. Van Couvering, La faune de rongeurs de Librilla. Corrélatons avec les formations marines du Miocène terminal et les datations radiométriques du volcanisme de Barqueros (Province de Murcia, Espagne méridionale), *C.R. Acad. Sci. Paris* 281 (1975) 519–522.
- [12] J. Agustí, S. Moyà-Solà, J. Gibert, J. Guillén, M. Labrador, Nuevos datos sobre la bioestratigrafía del Neógeno continental de Murcia, *Paleontol. Evol.* 18 (1985) 83–93.
- [13] P. Mein, J. Agustí, Les Gisements de Mammifères neogenes de la zone Betique, *Doc. Trav. IGAL* 13 (1990) 81–84.
- [14] J. Agustí, M. Freudenthal, J.I. Lacombe, E. Martín Suárez, Mio–Pliocene transition in the Librilla section (Mula basin, Murcia, Spain), Global events and Neogene evolution of the Mediterranean, IX R.C.M.N.S. Congr., 1990, 15 pp.
- [15] H. De Bruijn, P. Mein, C. Montenat, A. Van de Weerd, Corrélatons entre les gisements de rongeurs et les formations marines du Miocène terminal d'Espagne méridionale, *Proc. Kon. Ned. Akad. Wetensch.* 78 (1975) 1–32.
- [16] P. Mein, G. Bizon, J.J. Bizon, C. Montenat, Le gisement de Mammifères de La Alberca (Murcia, Espagne méridionale). Corrélatons avec les formations marines du Miocène terminal, *C.R. Acad. Sci. Paris, Série D* 276 (1973) 3077–3080.
- [17] C. Sanz de Galdeano, Geologic evolution of the Betic Cordilleras in the Western Mediterranean Miocene to the present, *Tectonophysics* 172 (1990) 107–119.
- [18] C. Montenat, P. Ott d'Estevou, J. Rodríguez-Fernández, C. Sanz de Galdeano, Geodynamic evolution of the Betic

- Neogene intramontane basins (S and SE Spain), *Paleontol. Evol.* 2 (1990) 5–59.
- [19] C. Montenat, P. Ott d'Estevou, Eastern Betic Neogene basins — A review, *Doc. Trav. IGAL* 13 (1990) 9–15.
- [20] C. Sanz de Galdeano, Los accidentes y fracturas principales de las Cordilleras Béticas, *Est. Geol.* 39 (1983) 157–165.
- [21] F. Gauyau, R. Bayer, J.C. Bousquet, J.C. Lachaud, A. Lesquer, C. Montenat, Le prolongement de l'accident d'Alhama de Murcia entre Murcia et Alicante (Espagne méridionale). Resultats d'une étude géophysique, *Bull. Soc. Géol. Fr.* 19 (1977) 623–629.
- [22] P.G. Silva, D.L. Goy, C. Zazo, Características estructurales y geométricas de la falla de desgarre de Lorca–Alhama, *Geogaceta* 12 (1992) 7–10.
- [23] M. Crusafont, Observations à un travail de M. Freudenthal et P.Y. Sondaar sur des nouveaux gisements à *Hipparion* d'Espagne, *Proc. Kon. Ned. Akad. Wetensch. B* 68 (1965) 121–126.
- [24] V. Fahlbusch, Report on the international symposium on mammalian stratigraphy of the European Tertiary, *Newsl. Stratigr.* 5 (1976) 160–167.
- [25] H. De Bruijn, R. Daams, G. Daxner-Höck, V. Fahlbusch, L. Ginsburg, P. Mein, J. Morales, Report of the RCMNS working group on fossil mammals, *Reisenburg* 1990, *Newsl. Stratigr.* 26 (1992) 65–118.
- [26] N.D. Opdyke, P. Mein, E. Lindsay, A. Perez-González, E. Moissenet, V.L. Norton, Continental deposits, magnetostratigraphy and vertebrate paleontology, late Neogene of Eastern Spain, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 133 (1997) 129–148.
- [27] A. van de Weerd, Rodent faunas of the Mio–Pliocene continental sediments of the Teruel–Alfambra region, Spain, *Utrecht Micropaleontol. Bull. Spec. Publ.* 2, 1976, 217 pp.
- [28] P. Mein, E. Moissenet, R. Adrover, Biostratigraphie du Néogène Supérieur du bassin de Teruel, *Paleontol. Evol.* 23 (1990) 121–139.
- [29] J. Agustí, M. Llenas, The late Turolian mureoid rodent succession in eastern Spain, *Acta Zool. Cracov.* 39 (1996) 47–56.
- [30] J.J. Jaeger, N. López Martínez, J. Michaux, L. Thaler, Les faunes de micromammifères du Néogène supérieur de la Méditerranée occidentale. Biochronologie, corrélations avec les formations marines et échanges intercontinentaux, *Bull. Soc. Géol. Fr.* 7 (1977) 501–506.
- [31] H. Thomas, R.L. Bernor, J.J. Jaeger, Origines du peuplement mammalien en Afrique du Nord durant le Miocène terminal, *Geobios* 15 (1982) 283–297.
- [32] C. Montenat, M. Crusafont, Découverte de mammifères dans le Néogène et le Pléistocène du levant espagnol (provinces d'Alicante et de Murcia), *C.R. Acad. Sci. Paris* 270 (1970) 3194–3197.
- [33] M.T. Alberdi, J. Morales, S. Moyà-Solà, B. Sanchiz, Macrovertebrados (reptilia y mammalia) del yacimiento finimioceno de Librilla (Murcia), *Est. Geol.* 37 (1981) 307–312.
- [34] J. Morales, D. Soria, E. Aguirre, Camélido finimioceno en Venta del Moro Primera cita para Europa occidental, *Est. Geol.* 36 (1980) 139–142.
- [35] M. Pickford, J. Morales, D. Soria, First fossil camels from Europe, *Nature* 365 (1993) 701.
- [36] M. Benammi, B. Orth, M. Vianey-Liaud, Y. Chaimanee, V. Suteethorn, G. Feraud, J. Hernandez, J.J. Jaeger, Micromammifères et biochronologie des formations néogènes du flanc sud du Haut-Atlas Marocain: implications biogéographiques, stratigraphiques et tectoniques, *Afr. Geosci. Rev.* 2 (1995) 279–310.
- [37] M. Benammi, M. Calvo, M. Prévot, J.J. Jaeger, Magnetostratigraphy and paleontology of Ait Kandoula basin (High Atlas, Morocco) and the African–European late Miocene terrestrial fauna exchanges, *Earth Planet. Sci. Lett.* 145 (1996) 15–29.
- [38] P.L. McFadden, M.W. McElhinny, Classification of the reversal test in paleomagnetism, *Geophys. J. Int.* 103 (1990) 725–729.
- [39] P. Lukowski, A. Poisson, Le bassin de Fortuna, *Doc. Trav. IGAL* 13 (1990) 303–311.
- [40] J.L. Kirschvink, The least-squares line and plane and the analysis of paleomagnetic data, *Geophys. J. R. Astron. Soc.* 62 (1980) 699–718.
- [41] F. Gautier, G. Clauzon, J.P. Suc, J. Cravatte, D. Violanti, Age et durée de la crise de salinité messinienne, *C. R. Acad. Sci. Paris* 318 (1994) 1103–1109.
- [42] S. Sen, J.P. Valet, Magnetostratigraphy of late Miocene continental deposits in Samos, Greece, *Earth Planet. Sci. Lett.* 80 (1986) 167–174.
- [43] R.L. Bernor, N. Solounias, C.C.I. Swisher, J.A. van Couvering, The correlation of three classical 'Pikermian' mammal faunas — Maragheh, Samos and Pikermi — with the European MN unit system, in: R.L. Bernor, V. Fahlbusch, H.W. Mittmann (Eds.), *The Evolution of Western Eurasian Neogene Mammal Faunas*, Columbia University Press, New York, 1996, pp. 137–154.
- [44] F.F. Steininger, W.B. Berggren, D.V. Kent, R.L. Bernor, S. Sen, J. Agustí, Circum Mediterranean Neogene (Miocene and Pliocene) marine–continental chronologic correlations of European mammal units and zones, in: R.L. Bernor, V. Fahlbusch, H.W. Mittmann (Eds.), *The Evolution of Western Eurasian Neogene Mammal Faunas*, Columbia University Press, New York, 1996, pp. 7–46.
- [45] J. Rodríguez-Fernández, J. Fernández, A.C. Lopez Garrido, C. Sanz de Galdeano, The central sector of the Betic Cordilleras, a realm situated between the Atlantic and Mediterranean domains during the upper Miocene, *Ann. Géol. Pays Hell.* 32 (1984) 97–103.
- [46] J. Rodríguez-Fernández, C. Sanz de Galdeano, Onshore Neogene Stratigraphy in the North of the Alboran Sea (Betic Internal Zones): Paleogeographic implications, *Geo-Mar. Lett.* 12 (1992) 123–128.
- [47] J.M. Soria, Evolución sedimentaria y paleogeográfica durante el Mioceno superior en el borde norte de la cuenca de Guadix, Cordillera Bética Central, *Est. Geol.* 50 (1994) 59–69.
- [48] D. Suk, D.R. Peacor, R. Van der Voo, Replacement of pyrite framboids by magnetite in limestone and implications for paleomagnetism, *Nature* 345 (1990) 611–613.