Available online at www.sciencedirect.com
ScienceDirect
PALAEO
Palaeogeography, Palaeoclimatology, Palaeoecology 252 (2007) 601 – 616
www.elsevier.com/locate/palaeo

Palynological evidence for astronomical forcing in Early Miocene lacustrine deposits from Rubielos de Mora Basin (NE Spain)

Gonzalo Jiménez-Moreno [a,b,*], Hayfaa Abdul Aziz [c], Francisco J. Rodríguez-Tovar [b], Eulogio Pardo-Igúzquiza [d], Jean-Pierre Suc [a]

[a] *Laboratoire PaléoEnvironnements et PaléobioSphère (UMR CNRS 5125), Université Claude Bernard- Lyon 1, bâtiment Géode, 27-43 boulevard du 11 Novembre, 69622 Villeurbanne Cedex, France*
[b] *Departamento de Estratigrafía y Paleontología, Universidad de Granada, Avda. Fuente Nueva S/N, 18002 Granada, Spain*
[c] *Department of Earth and Environmental Sciences, Geophysics LMU Munich, Theresienstr. 41 D-80333 Munich, Germany*
[d] *Departamento de Geodinámica, Universidad de Granada, Avda. Fuente Nueva S/N 18002, Granada, Spain*

Received 25 January 2007; received in revised form 15 May 2007; accepted 29 May 2007

Abstract

Pollen and paleomagnetic analysis of the Rubielos de Mora-1 core (Rubielos de Mora basin, NE Spain) has been carried out with the aim of reconstructing floral, vegetational and climatic changes within an accurate time framework. Based on biostratigraphic information, the magnetostratigraphy of the Rubielos de Mora-1 core is calibrated to the Astronomical Tuned Neogene Time Scale (ATNTS04) resulting in an age of Early Miocene for the cored sedimentary sequence. The high percentages of thermophilous taxa and the diverse subarid flora in the pollen spectra points to a very dry subtropical climate with a marked seasonality, reflecting the onset of the Miocene climatic optimum. On the other hand, taxa with high water requirements (riparian) are also abundant. Alternation in pollen taxa (thermophilous *vs*. mesothermic–riparian), coincide with sedimentological changes, which are related to lake level fluctuations and vegetation changes. In turn, the vegetational pattern indicates cyclic changes in temperature and precipitation which is controlled by astronomically forced obliquity cycles.

Keywords: Vegetation; Magnetostratigraphy; Climate; Early Miocene; NE Spain

1. Introduction

The lacustrine sediments of the Early Miocene from the Rubielos de Mora basin show a distinct oxic–anoxic cyclicity together with finer scale cyclicity within the laminated anoxic sediments (rhythmites) (Anadón et al., 1988a, 1991). The sediments contain a very rich and well-preserved fossil fauna that has been extensively studied in several outcrops throughout the basin (Crusafont-Pairó et al., 1966; de Bruijn and Moltzer, 1974; Martínez-Delclòs et al., 1991; Montoya et al., 1996; Montoya, 2002; Peñalver et al., 2002; Peñalver and Martínez-Delclòs, 2003). Nevertheless, biostratigraphic data is not well-constrained and the only age control in the basin comes from two mammal sites of about the same Early Miocene age (Crusafont-

* Corresponding author. Present address: Department of Earth and Planetary Sciences, Northrop Hall, University of New Mexico, Albuquerque, NM 87131 and Center for Environmental Sciences & Education, Box 5694, Northern Arizona University, Flagstaff, AZ 86011, USA. Tel.: +1 505 265 7709; fax: +1 505 277 8843.
E-mail addresses: gonzaloj@ugr.es, Gonzalo.Jimenez-Moreno@NAU.EDU (G. Jiménez-Moreno).

0031-0182/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.palaeo.2007.05.013

Pairó et al., 1966; de Bruijn and Moltzer, 1974; Montoya et al., 1996). Therefore, a better age control of the sedimentary sequence is needed.

Preliminary studies of the micro- and macrofloras have been carried out in the Rubielos de Mora basin (Fernández Marrón and Álvarez-Ramis, 1988; Álvarez Ramis and Fernández Marrón, 1994; Barrón and Sansisteban, 1999; Roiron et al., 1999; Rubio et al., 2003). They show vegetation dominated by mesothermic and riparian plants indicative of a humid temperate climate. In contrast, micro- and macroflora studies from other nearby basins for the same temporal interval have identified several very warm and subdesertic taxa of the family Caesalpiniaceae (*Banksia*, *Caesalpinia*, *Cassia*), Mimosaceae (*Acacia*, *Mimosa*) and Proteaceae (*Grevillea*, *Protea*) (Bessedik, 1985; Sanz de Siria Catalán, 1993; Jiménez-Moreno, 2005). Therefore, vegetation and climate of the Early Miocene in Southwestern Europe still remains unclear.

The influence of astronomical (Milankovitch) forcing on the vegetation has been recognized in pollen records of the Pliocene and Late Miocene (Combourieu-Nebout and Vergnaud-Grazzini, 1991; Bertini, 2001; Popescu, 2001; Popescu et al., 2006; Kloosterboer-van Hoeve et al., 2006) but is still lacking in the Early Miocene records. In order to fill this gap, recently, Jiménez-Moreno et al. (2005) revealed the usefulness of pollen analysis to detect Milankovitch induced climatic fluctuations in Middle Miocene sediments from Hungary.

The drilling of a 365 m long core (Rubielos de Mora-1) in the western part of the Rubielos de Mora basin has allowed us to carry out an extensive sampling for pollen and paleomagnetic analysis of the Early Miocene sedimentary sequence. The quantitative analysis of the pollen data has been used to characterize the observed sedimentary cyclicity in terms of repetitive changes in vegetation. Together with an accurate age control, paleoenvironmental and climatic changes have been reconstructed, and the influence of astronomically forced climate changes on the origin and evolution of the vegetation in the Rubielos de Mora basin has been evaluated.

2. Geological and stratigraphical setting

The studied area is located within the Rubielos de Mora Basin, in the southernmost part of the linking zone between the eastern Iberian Chain and the Catalán Coastal Ranges (Fig. 1). During the Early Miocene, tectonic subsidence led to the development of a relatively deep lacustrine system where anoxic bottom water conditions prevailed favoring the preservation of fossils and organic-rich sediments (Anadón et al., 1989). The presence of two mammal sites, RM-1 and RM-2 (Crusafont-Pairó et al., 1966; de Bruijn and Moltzer, 1974; Montoya et al., 1996), in the upper part (Upper Unit) of the sedimentary sequence permitted dating of the basin-fill as Early Miocene's local Ramblian (MN3; Montoya et al., 1996) or Aragonian (MN4; López-Martínez, 1989; de Bruijn et al., 1992) on the basis of Eomyidae (Alvarez Sierra, 1987) and Lagomorpha (López-Martínez, 1989). One of the fossil sites, the mammal locality RM-2, is located close to the drilling site.

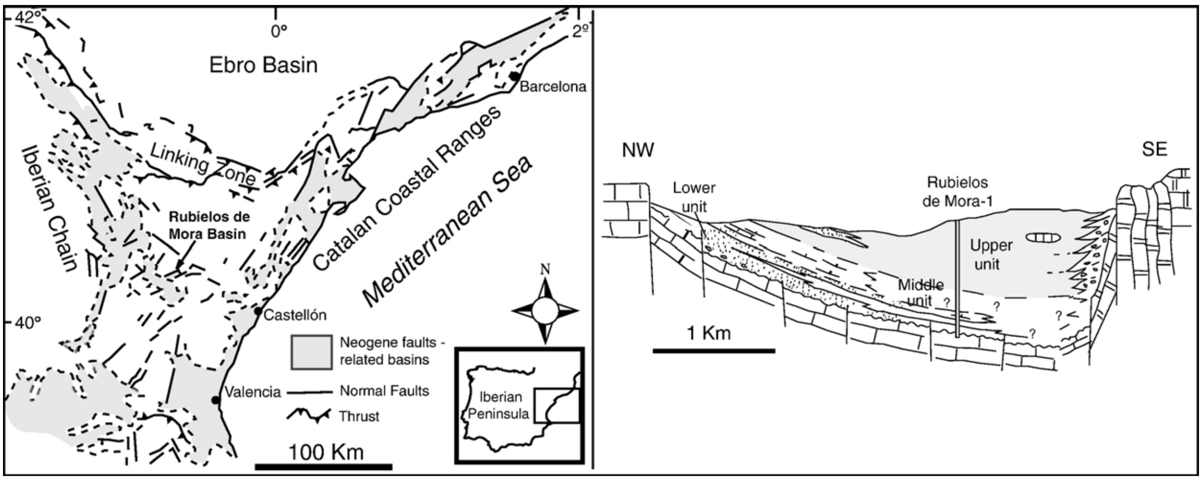

Fig. 1. Location of the borehole Rubielos de Mora-1 and main structural units in NE Spain (Left). Subdivision of the Rubielos de Mora basin fill in three units (modified from Anadón et al. (1988b) (Right).

Three stratigraphic units have been distinguished in the basin (Anadón et al., 1988a,b, 1989, 1991):

Lower unit. It is made up of a 300 m thick sequence of sandstones interbedded with mudstones and some conglomerates of reddish–yellowish color. They have a fluvial origin and discordantly overlay Cretaceous sediments ("Weald" and "Utrillas" facies).

Middle unit. It comprises a 100 m thick unit of mainly lacustrine sediments. Lignites are abundant in the eastern part of the basin while fluviatile sediments dominate in the western part. This unit represents an early stage development of a lake in the basin.

Upper unit. This unit is up to 400 m thick and mainly consists of open lacustrine sediments but also a large variety of other facies. In the western part, the lacustrine facies is characterized by oxic–anoxic cyclical sequences of massive clays (oxic facies) and dark laminated clays (anoxic facies) (Fig. 2). Each cycle is about 0.6–9 m thick and is the product of alternating periods of anoxic and well-oxygenated lake bottom conditions (Anadón et al., 1988a). The laminated (anoxic) facies, comprises sandy mudstones, mudstones with bioclastic lamination, oil-shales, rhythmites and marls. These sediments were deposited during high lake level stages, where permanently stratified (meromictic) and anoxic bottom conditions prevailed (Fig. 2). The rhytmites are characterized by an alternation between fine carbonate precipitates (calcite and aragonite) and terrigenous marls. They formed as a result of small lake level fluctuations, mainly due to changing water inputs (Anadón et al., 1988a; Fig. 2).

The green-grey massive claystones were deposited in oxygenated lake water. The claystones are rich in carbonates and especially low in magnesium calcite and dolomite which was probably linked to an increase in the evaporation which generated alkaline conditions in the lake waters (Anadón et al., 1988a). Root bioturbation is common while evaporitic saline or desiccation features are absent inferring permanent lake conditions.

A new cycle starts with a water influx into the lake, generating a detrital episode (Fig. 2). This lacustrine "transgression" resulted in an increase in the volume of the lake. Subsequently, the waters in the lake became stratified resulting in the deposition of the laminated facies.

The mega-sequential sedimentological organization in this basin, characterized by the superposition of the three units, indicates steps in the development of a lake. The deepening trend was mainly influenced by synsedimentary tectonics (Anadón et al., 1988b).

3. Rubielos de Mora-1 core

The 386.5 m-long core was drilled by the Sociedad Española de Talcos, S.A., and U.S. Borax slightly north of the Cerro del Porpol and close to the village of Rubielos de Mora (40°11′13 N; 0°42′08 W) (Fig. 1). The average core recovery is 72%, and the three main lithological units in the basin, as described by Anadón et al. (1988a,b, 1989), were drilled. The poorly recovered intervals and gaps in the core are mainly associated with sandy lithologies whilst the best recovered intervals dominantly comprise clayey and silty intervals.

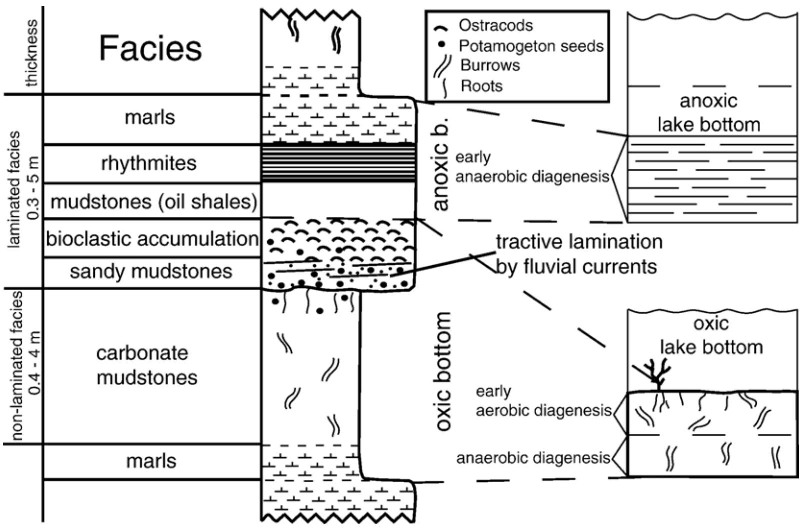

Fig. 2. Main sedimentological features and interpretation of an ideal cycle between anoxic–oxic bottom conditions in the western part of the Rubielos de Mora basin [modified from Anadón et al. (1988a)].

4. Magnetostratigraphy

4.1. Methods

Samples were taken and air-drilled from selected pieces of the Rubielos de Mora-1 core at an average interval of 1.7 m (Fig. 3). The characteristic remanent magnetisation (ChRM) was determined by thermal demagnetization of the samples in a laboratory-built shielded furnace using incremental heating steps of 30 °C. The natural remanent magnetization (NRM) was measured on a horizontal 2G Enterprises DC SQUID cryogenic magnetometer (noise level 3×10^{-12} Am^2) at the Paleomagnetic Laboratory Fort Hoofddijk in Utrecht, the Netherlands. NRM directions were determined using principal component analysis after Kirschvink (1980). Since no orientation is available for the studied cores, declination control is lacking and interpretation of the ChRM is based on the inclination value only. The geocentric axial dipole (GAD) inclination for the drilling site of the Rubielos de Mora core is 55°, which is steep enough to allow unambiguous polarity determination.

4.2. Results

The thermal demagnetization, Zijderveld, diagrams are of reasonably good quality. NRM intensities vary between 0.03 and 55 mA/m (average 8 mA/m) with only a few samples showing markedly higher intensities ranging from 80 to 215 mA/m. Zijderveld diagrams and intensity decay curves show that most samples comprise two and a few samples three components (Fig. 3B–E). The first component shows a random oriented, viscous, direction, which is removed at 100 °C. This component represents a laboratory-induced magnetization related to storage. The rarely observed second component has a normal directed inclination which is removed between temperatures of 180–240 °C. This second component is often found in samples with weak intensities. The third component is removed at around 420 °C and shows in the Zijderveld diagrams a linear trend pointing to the origin. We interpret this component as the characteristic remanent magnetization (ChRM). The unblocking temperatures of 390–420 °C suggest that iron sulfides are the main carrier of the ChRM magnetization. A few samples show, when heated at temperatures higher than 360 °C, a significant progressive increase in the intensity indicating the oxidation of iron sulfide. The presence of iron sulfides in these samples suggests that reduced bottom water conditions prevailed during deposition of the lake sediments.

The ChRM directions were calculated for 5 to 7 temperature steps in the range 240–420 °C. The quality of the measurements and the line fitting (without anchoring to the origin) was evaluated by visual inspection of the Zijderveld diagrams and by calculating the maximum angular deviation (MAD; Fig. 3). The MAD is generally low (mean 10°) indicating good data quality. The average inclination for the reversed samples is 55° (N=57) and for the normal 58° (N=43). However, they have not been corrected because of a lack of orientation for the dip of the strata and core drilling direction.

4.3. Calibration to the ATNTS04

ChRM inclination values (excluding non-interpretable directions), MAD angles and initial intensity are plotted with core depth revealing the presence of several polarity reversals for the Rubielos de Mora-1 core (Fig. 3A). Using the biostratigraphic information from the fossil localities found in the basin, RM-1 and RM-2, and unpublished magnetostratigraphic results from a 65 m long field section in the study area, we attempt to correlate the magnetozones to the ATNTS04 (Lourens et al., 2004; Fig. 4A–B). The lithological variation observed in the field section can be correlated, though not bed-to-bed, to similar variations in the Porpol area in which the fossil site of RM-2 is located (de Bruijn and Moltzer, 1974). The youngest locality RM-1 lies in the same area as RM-2 but at a topographic (and stratigraphic) higher level. The lithological succession of the upper part of the Rubielos de Mora-1 core (i.e., between 90 and 150 m) has similar characteristics as observed in the field and Porpol successions. As a consequence, fossil site RM-1 would likely correspond to the uppermost part of the Upper Unit of Rubielos de Mora-1 core while RM-2 to the lower part of this Unit (Fig. 3). In this way an indirect correlation of the fossil localities to the core is established. It must be noted that due to lack of control on lateral facies variations (and possible faults), no bed-to-bed correlation could be achieved and hence the fossil levels in the core are only relative positions. Nevertheless, the paleomagnetic analysis results of the field section yielded a long reversal with a normal polarity at the top and bottom end of the measured section (unpublished). This pattern is similar to the magnetostratigraphic record of Upper Unit of the Rubielos de Mora-1 core suggesting that the correlation is reliable.

On the basis of the small-mammal fossil fauna Eomyidae (Alvarez Sierra, 1987) and Lagomorpha (López-Martínez, 1989), the fossil localities RM-1 and RM-2 can be constrained to local Zones A–C that correspond to Mammal Neogene zones "later" MN3 or MN4 (Early Aragonian to Ramblian; J. van Dam,

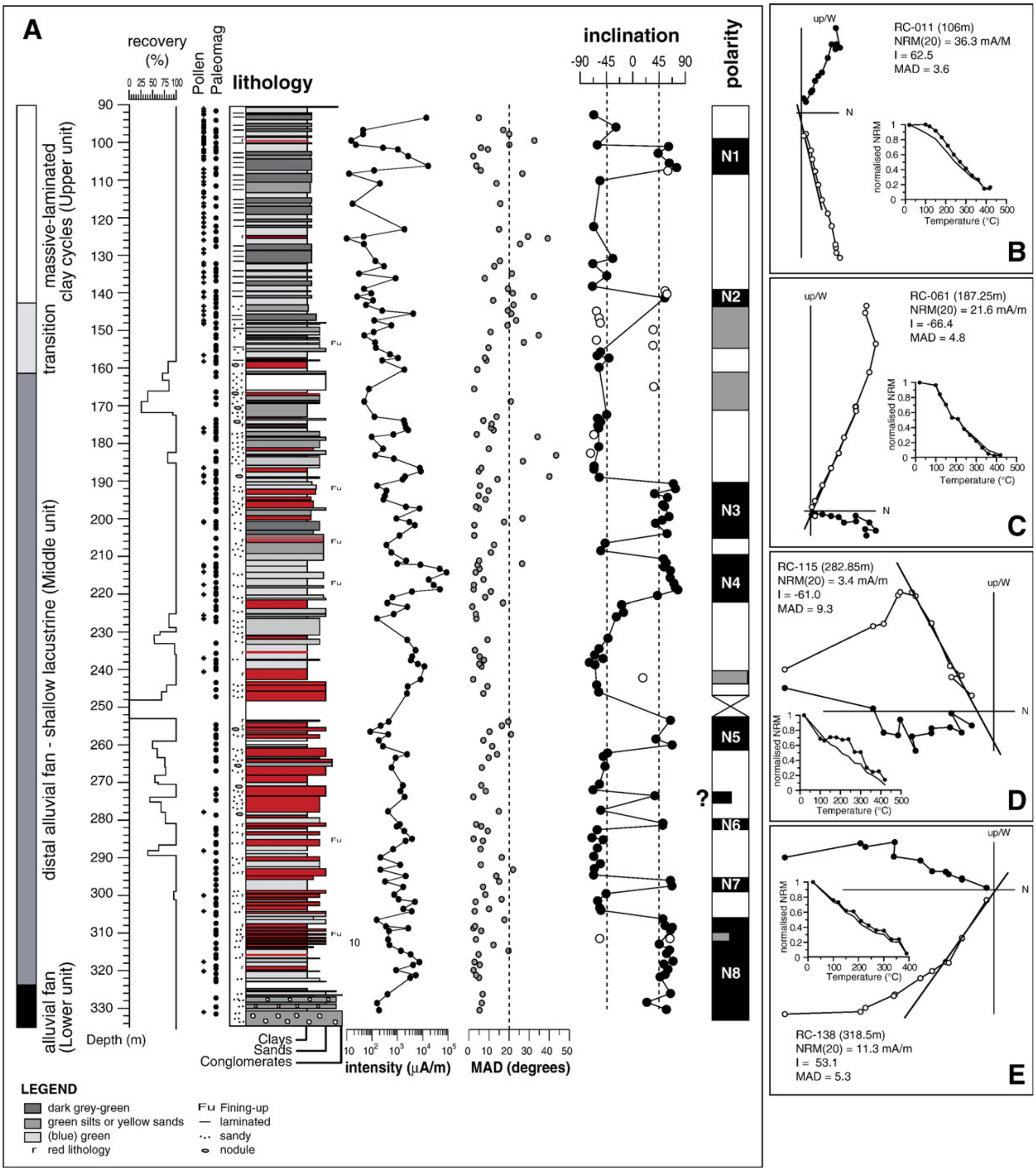

Fig. 3. (A) Geological log of the studied part of the Rubielos de Mora-1 core with subdivision in the three units by Anadón et al. (1988a). The pollen and paleomagnetic sample positions and estimated core recovery are shown next to the lithological log. An explanation of the different features of the lithological column is shown in the legend. The paleomagnetic results include initial intensity, MAD [maximum angular deviation], inclination and interpreted polarity. The closed (open) symbols in the inclination record represent reliable (unreliable) charactristic remanant magnetization directions. In the polarity record, black (white) indicates normal (reverse) polarity. The gray shaded zones indicate unclear polarity. (B–E) Thermal demagnetization diagrams of selected samples from the Rubielos de Mora core. Black (white) denotes projection in vertical (horizontal) scale. The thermal steps are 20, 100 and subsequently 30 °C steps from 120 to 420 °C. Inset diagrams show the decay curves of the sample. For each sample, the initial intensity (NRM(20)), inclination value (I) and MAD have been indicated.

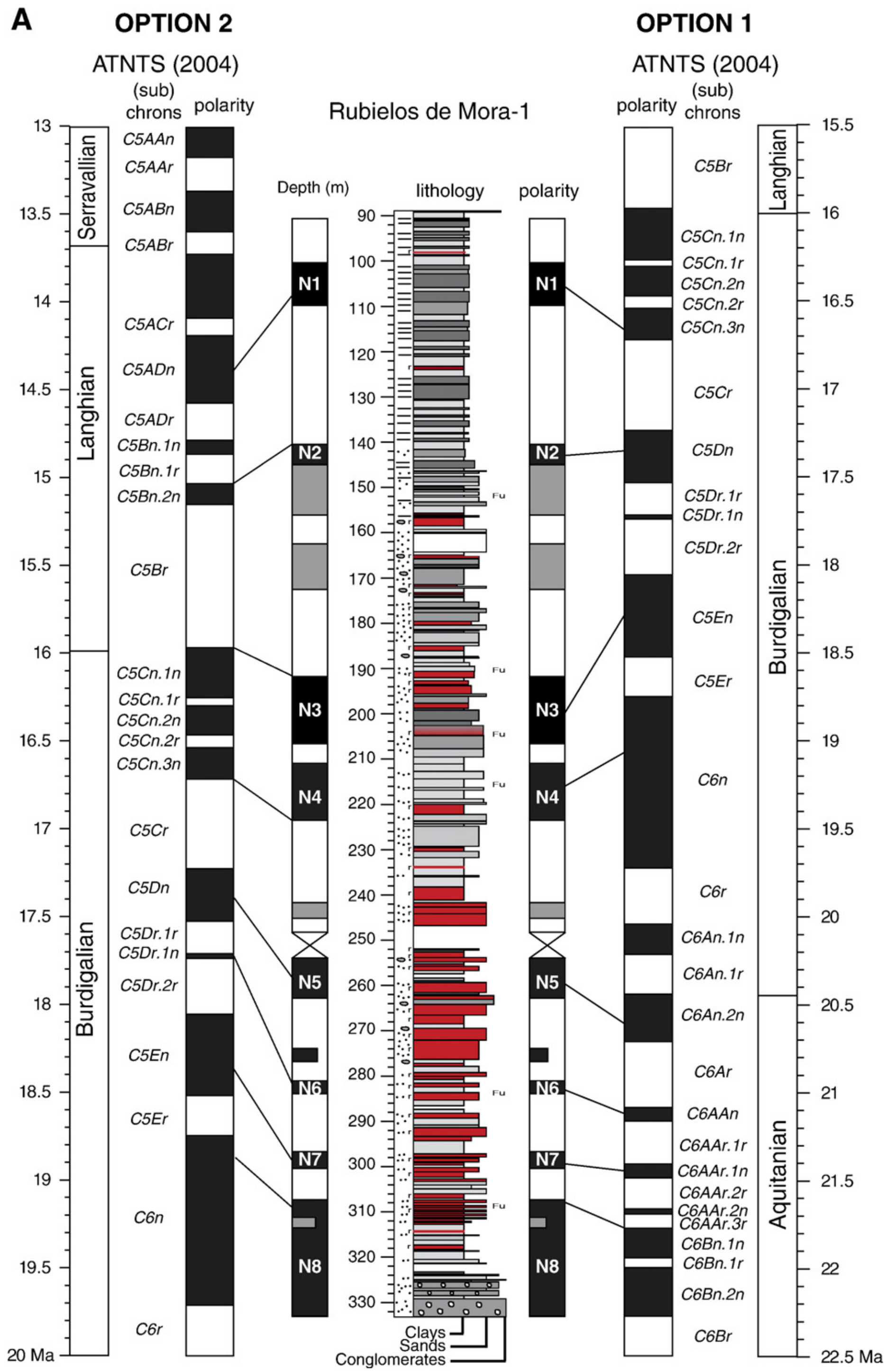

Fig. 4. A. Correlation options 1 and 2 of the Rubielos magnetostratigraphic record to the Astronomical Tuned Neogene Time Scale (Lourens et al., 2004). For details of the lithological column, see caption. B. Correlation option 3 of the Rubielos magnetostratigraphic record to the Astronomical Tuned Neogene Time Scale (Lourens et al., 2004) and CK95 (Cande and Kent, 1995) timescales. Insets, sedimentation rates (according to ATNTS04 timescale) for the different correlation options, see text for details.

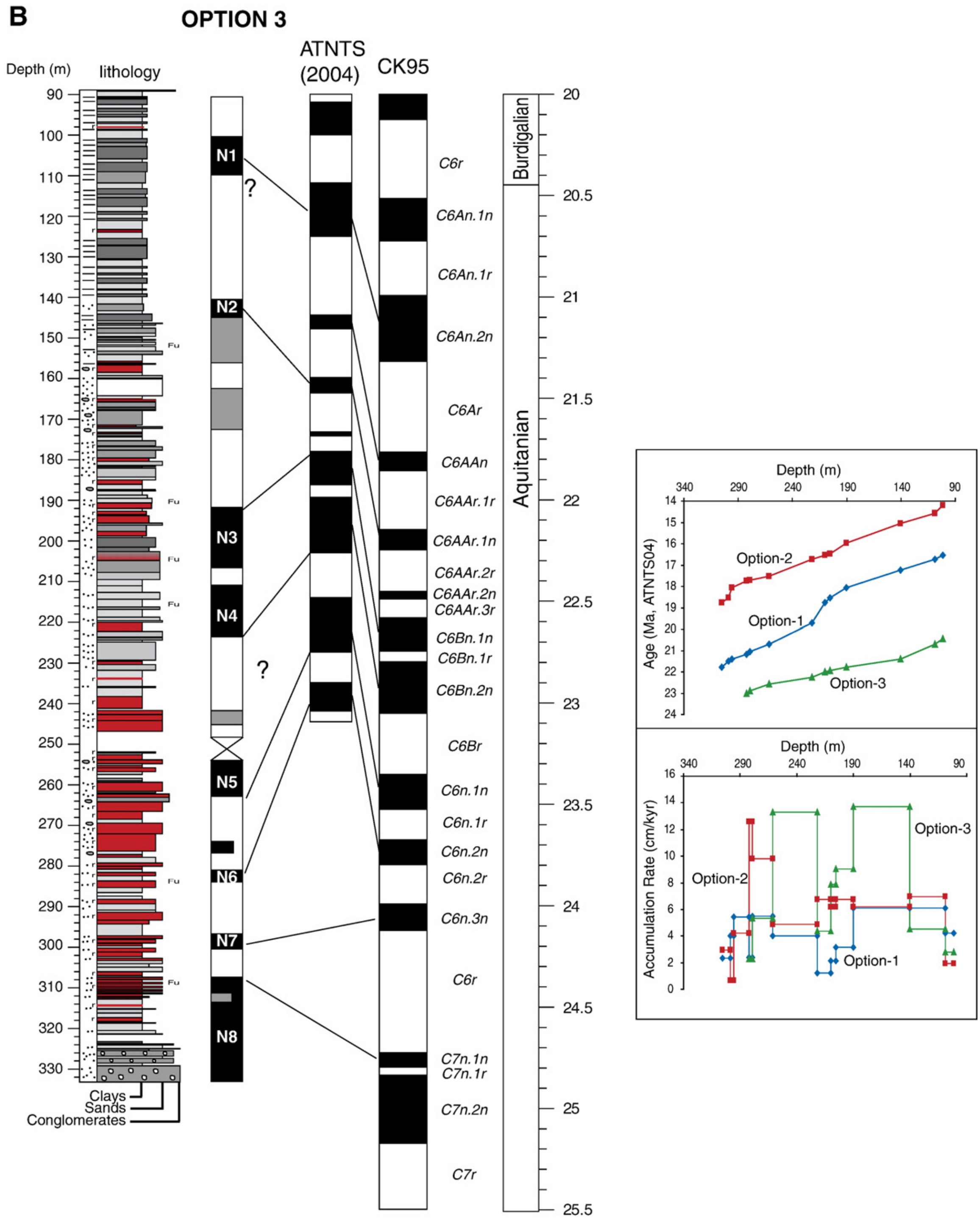

Fig. 4 (*continued*).

personal communication). This MN zonation suggests an age between 19.6 and 15.9 Ma (Larrasoaña et al., 2006) for the Upper Unit in the Rubielos de Mora-1 core.

4.3.1. Correlation options

Taking into account the biostratigraphic age estimation and the above described stratigraphic information, we correlate the magnetozone N1 to C5Cn.3n. The

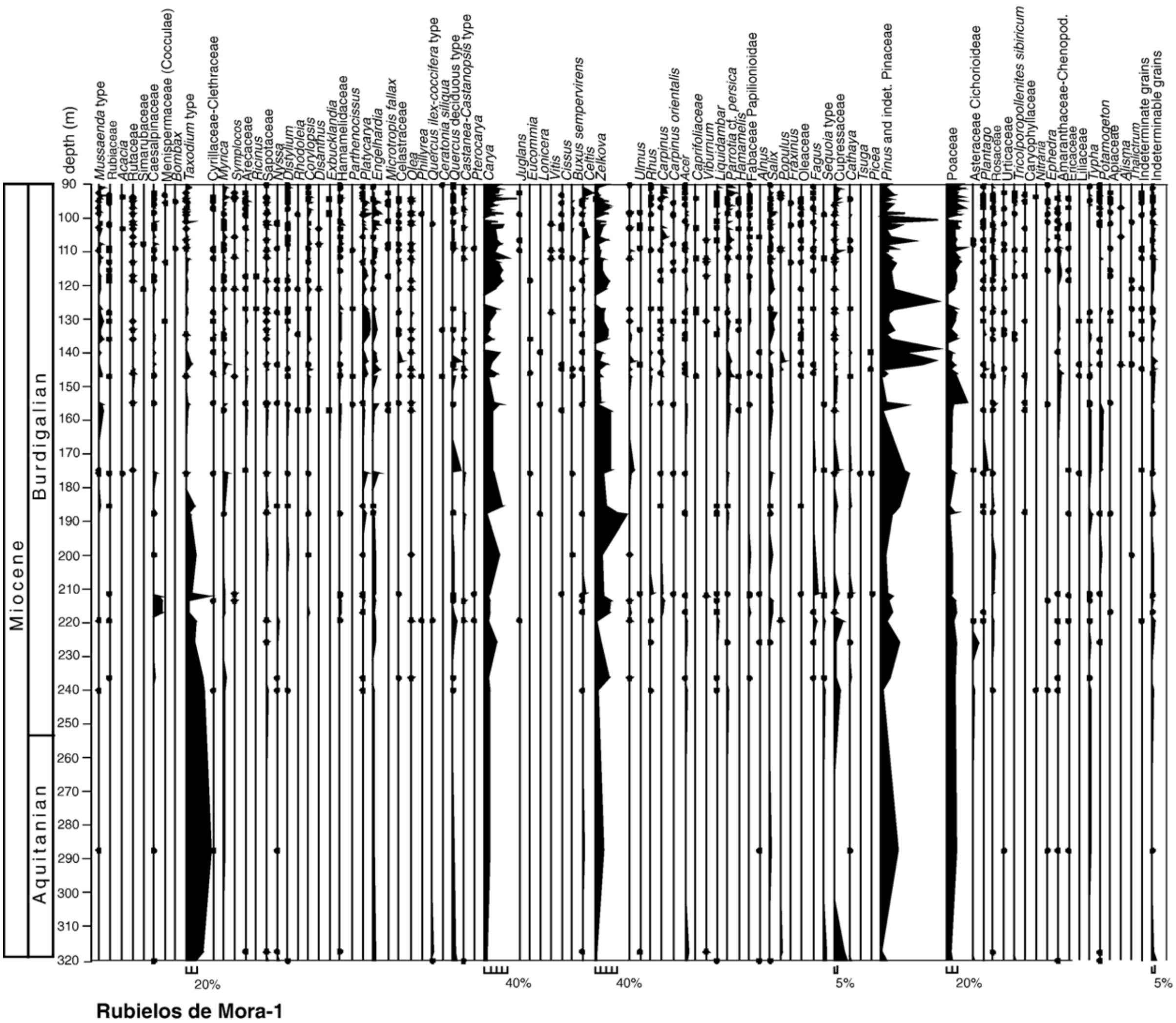

Fig. 5. Detailed simplified pollen diagram without *Pinus* and indeterminable Pinaceae of the studied part of the Rubielos de Mora-1 core. Black dots indicate percentages lower than 1%.

poorly defined normal magnetozone N2 is correlated to C5Dn (Fig. 4A). We presume that the low sampling resolution (average 1.7 m) fails to register the subchrons with a short duration such as subchron C5Dr.1n and therefore it is not found in the magnetostratigraph record of the core. The magnetozones N3 and N4 are correlated to C5En and C6n, respectively. The subsequent correlation to the ATNTS04 is hampered by the poor core recovery between 230 and 252 m depth and the presence of a core gap around 250 m. We therefore assume that subchron C6An.1n is not found in the Rubielos de Mora record and correlate N5 to C6An.2n. Consequently, magnetozones N6 and N7 are correlated to subchrons C6AAn and C6AAr.2r, respectively. Finally, N8 is correlated to C6Bn.1n.

This magnetostratigraphic calibration to the ATNTS04 is not unambiguous because of the presence of gaps and poor recovery in certain intervals of the core, therefore, a second correlation option (option-2 in Fig. 4A) is presented. Option-2 involves the correlation of magnetozone N1 to C5ADn. Similarly as above, we presume that CBn.1n is not registered in the core and that N2 likely correlates to CBn.2n. The following magnetozones N3, N4, and N5 are correlated to C5Cn.1n, C5Cn.3n, and C5Dn, respectively. Correlation of N6 to N8 to respectively C5Dn, C5Dr.1n and C5En does not seem straightforward. The sandier interval of this Middle Unit could possibly account for changing sedimentation rates (due to erosion) and hence influence the duration of the

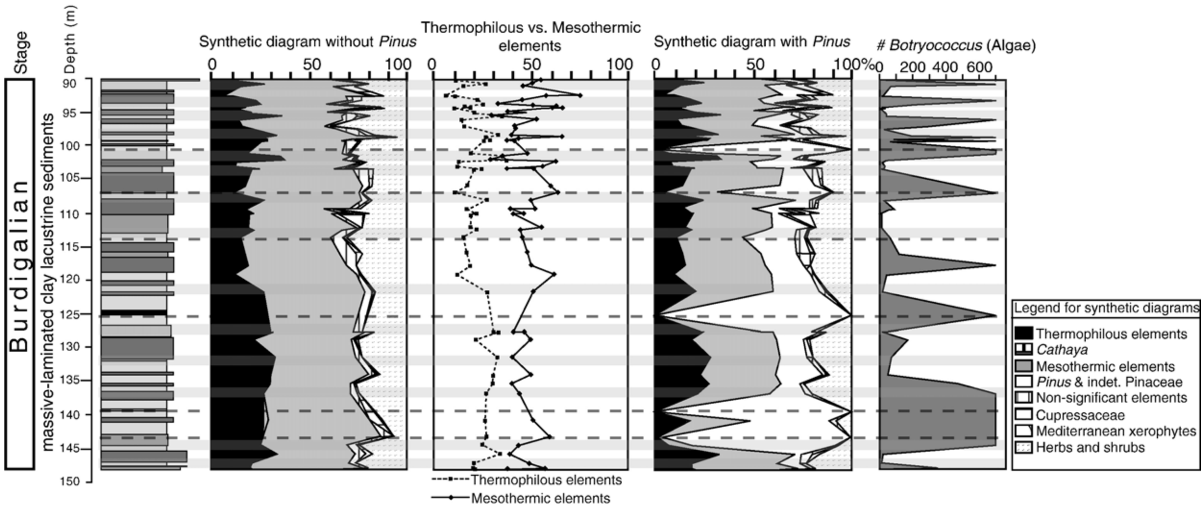

Fig. 6. Comparison between the geological log, the pollen synthetic diagram with and without *Pinus* and indeterminable Pinaceae, the sequential variations of the relative abundance of thermophilous and mesothermic elements and the abundance of *Botryococcus* (Algae) in the lacustrine facies (uppermost part) of the core Rubielos de Mora-1. Ages based on the correlation with the ATNTS04 (Lourens et al., 2004). Shaded areas and dashed lines represent coincidences between the massive clays with high percentages of thermophilous elements, *Pinus* and indeterminable Pinaceae and *Botryococcus*. Grouping for the synthetic diagram was made regarding the ecology of the plants (Nix, 1982); (1) thermophilous elements: *Acacia*, Acanthaceae, *Alchornea*, *Bombax*, *Buxus bahamensis* type, Caesalpiniaceae, *Croton*, Euphorbiaceae, Mappianthus, Rubiaceae, *Mussaenda* type, *Fothergilla*, Meliaceae, Menispermaceae, Rutaceae, Simarubaceae, *Taxodium* type, Chloranthaceae, *Rhoiptelea*, *Microtropis fallax*, Celastraceae, Araliaceae, *Parthenocissus*, *Platycarya*, *Engelhardia*, *Exbucklandia*, Hippocastanaceae, *Rhodoleia*, *Corylopsis*, *Disanthus*, Sapotaceae, *Nyssa*, *Distylium*, Arecaceae, *Ricinus*, *Symplocos*, *Symplocos paniculata* type, Cyrillaceae–Clethraceae, Taxodiaceae, Theaceae; (2) *Cathaya*; (3) mesothermic elements: *Fagus*, *Quercus* deciduous type, Castanea–Castanopsis type, *Sequoia* type, *Fraxinus*, Oleaceae, Hamamelidaceae, *Myrica, Betula*, *Salix*, *Populus*, *Hamamelis*, Fabaceae Papilionioidae, *Alnus*, Caprifoliaceae, *Viburnum*, *Liquidambar*, *Parrotia* cf. *persica*, *Hedera*, Rhamnaceae, *Acer*, *Ilex*, *Platanus*, *Ulmus*, *Rhus*, *Carpinus*, *Carpinus orientalis*, *Ostrya*, *Buxus sempervirens*, *Celtis*, *Zelkova*, *Juglans*, *Eucommia*, *Lonicera*, *Vitis*, *Cissus*, Pterocarya, Carya; (4) *Pinus* and indeterminable Pinaceae; (5) Non-significant elements: Rosaceae, Ranunculaceae, non identified pollen grains, etc.; (6) mediterranean xerophytes: *Quercus ilex-coccifera* type, *Olea* and *Phillyrea*; (7) herbs and shrubs: Poaceae, Nymphaeaceae, *Thalictrum*, Apiaceae, *Alisma*, Liliaceae, *Typha*, *Potamogeton*, Ericaceae, Ranunculaceae, *Ephedra*, Amaranthaceae–Chenopod., *Nitraria*, *Parietaria*, Resedaceae, Convolvulaceae, Urticaceae, Campanulaceae, *Tricolporopollenites sibiricum*, Caryophyllaceae, Lamiaceae, *Mercurialis*, Rosaceae, Plumbaginaceae, *Geranium*, *Linum*, *Tamarix*, Polygonaceae, *Rumex*, Brassicaceae, Cistaceae, Asteraceae Asteroideae, Asteraceae Cichorioideae, *Plantago*.

subchrons registerd in the magnetostratigraphic record of the Rubielos de Mora-1 core.

Finally, a third and older correlation of the magnetostratigraphic record is shown in Fig. 4B. Since the ATNTS04 is only constructed up to the Paleogene, we also show part of the correlation according to the GPTS of CK95 (Cande and Kent, 1995). The magnetostratigraphic record of Rubielos de Mora-1 core allows the following correlation (see Fig. 4B): magnetozone N1 to C6An.2n, N2 to C6AAr.1n thereby assuming the C6AAn is not registered in the core record and N3 and N4 are correlated to C6Bn.1n and C6Bn.2n, respectively again assuming that C6AAr.2n is not registered. Magnetozone N5 correlates to C6Cn.1n while N6 and N7 to C6Cn.2n and C6Cn.3n, the latter coorelated to CK95 timescale. Finally, N78 is correlated to C7n, assuming that the reversed C7n.1r is not found in the Rubielos de Mora-1 magnetostratigraphic record.

4.3.2. Sedimentation rates

The calibration to the ATNTS04 suggests that the recovered sediments from the Rubielos borehole either span a time interval from about 22 to 16.5 Ma (option-1), or 19 to 14.3 Ma (option-2) or 21 to more than 23 Ma (option-3) (Fig. 4A–B). The accumulation rates for correlation options 1 and 2 are more or less similar for the upper part of the Rubielos de Mora-1 core (Fig. 4B inset). Between 140 and 220 m depth, however, option-1 shows larger deviating rates corresponding to chron interval C5Dn to C6n while option-2 is, corresponding to interval C5Bn.2n to C5Cn.3n, is more constant. The opposite holds for depths 260 m and onwards, where option-2 shows larger changes in accumulation rates while option-1 is more constant. For the sake of comparison, the accumulation rates for option-3 are calculated only up to C6n.2n because the ATNTS04 has not yet been constructed for the Paleogene and, as can be seen in Fig. 4B, there is large differences in age

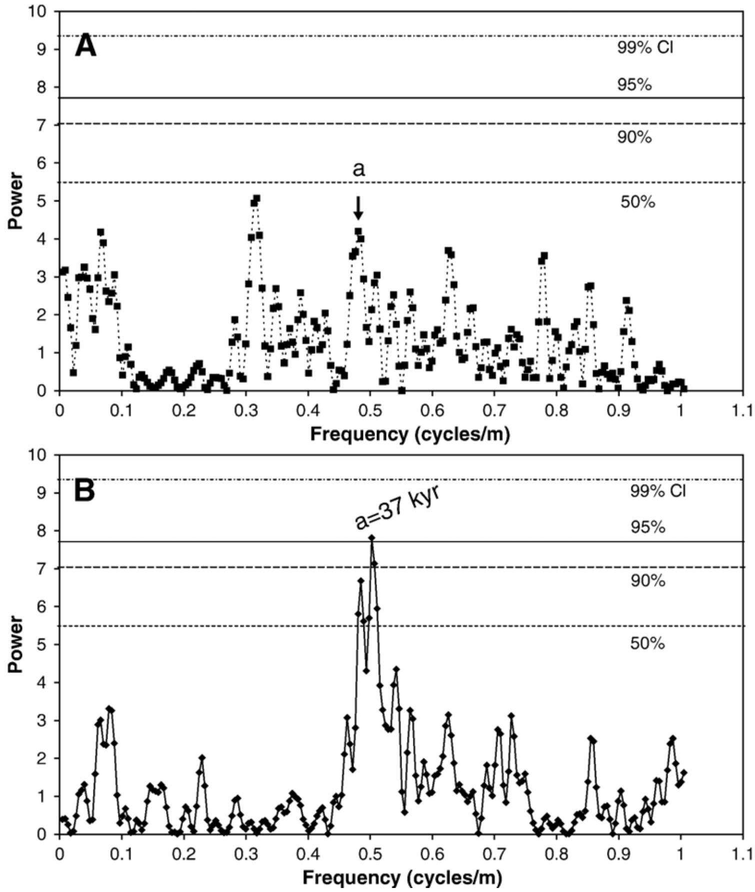

Fig. 7. Spectral analysis of the relative abundance of selected pollen groups in the Rubielos de Mora-1 core. (A) thermophilous elements; (B) mesothermic elements. Significant peaks are marked with the letter a.

and duration of (sub)chrons between the ATNTS904 and the GPTS of CK95 (Cande and Kent, 1995). Altogether, the sedimentation rates for option-3 are very irregular especially for the Upper Unit, which is considered as stable lake environment lacking hiatus. We conclude that the accumulation rates for option-3 are not appropriate, while the rates of option-1 and -2 do not provide additional information to further constrain the magnetostratigraphic correlation. The biostratigraphy, however, argues that option-1 is preferred because it better corresponds to the estimated MN ages (i.e., 19.6 and 15.9 Ma) than option-2, which is at least 1 to 3 Ma younger, and option-3, which is at least 2 Ma older.

5. Palynology

5.1. Methods

Eighty samples rich in palynomorphs have been studied. Most of the samples come from the lacustrine facies of the upper unit (Fig. 3). The conglomerates, sandstones and reddish claystones from the lower and middle units have not been sampled because palynomorphs do not usually preserve under oxidizing conditions. The samples were treated according to the following procedure: 15–20 g of sediment was processed with cold HCl (35%) and HF (70%), removing carbonates and silicates respectively. Separation of the palynomophs from the rest of the residue was carried out using $ZnCl_2$ (density = 2). Sieving was performed using a 10 μm nylon sieve. The pollen residue, mounted in glycerine, was prepared on slides. A transmitted light microscope, using ×250 and ×1000 (oil immersion) magnifications, was used for identification and counting of palynomorphs. Because of low representation, spores have not been considered. A minimum of 150 pollen grains (*Pinus* and indeterminable Pinaceae excluded) were counted in each analyzed sample (Cour, 1974).

A simplified detailed diagram (Fig. 5) and two standard synthetic diagrams (Suc, 1984) of the upper part of the core, with and without *Pinus* and Pinaceae (Fig. 6) have been plotted. To better visualize the composition of the past vegetation, taxa have been ordered into 9 different groups (Fig. 6) based on the following ecological criteria (Nix, 1982): (1) thermophilous (tropical and subtropical) elements; (2) *Cathaya*, a conifer today restricted to mid-altitude in tropical China; (3) mesothermic (warm-temperate) elements; (4) *Pinus* and indeterminable Pinaceae; (5) non-significant elements (without any climatic implications); (6) Cupressaceae; (7) Mediterranean xerophytes and (8) herbs and shrubs.

5.2. Results

Pollen spectra indicate a flora dominated by mesothermic riparian plants where *Carya* and *Zelkova* are the most abundant (Fig. 5). The thermophilous elements are very abundant in some samples and are represented mainly by *Engelhardia*, *Platycarya, Mussaenda* type (Rubiaceae), Hamamelidaceae, *Corylopsis*, *Distylium*, Caesalpiniaceae, Sapotaceae, Arecaceae, Celastraceae and *Acacia*. The group of herbs is relatively important in the pollen sum and is mainly made up of Poaceae, *Plantago,* Amaranthaceae–Chenopodiaceae, Apiaceae, Urticaceae and aquatic plants such as *Typha* and *Potamogeton*. In some samples, the presence of the subdesertic plant *Nitraria* is remarkable (Fig. 5). *Pinus* and indeterminable Pinaceae vary considerably along the core; from 1% to 100% of the total pollen sum. The algae *Botryococcus* shows a similar behavior and covaries with the abundance–scarcity variation of *Pinus* and indeterminable Pinaceae (Fig. 6).

A metre-scale cyclicity on the vegetation has been observed along the borehole and is mainly found within the lacustrine facies, in the upper part of the core and within the upper unit (see Figs. 2 and 6). Periods in which thermophilous plants and xerophytes (Caesalpiniaceae, *Acacia*, *Bombax*, *Nitraria*, *Alchornea*, *Ephedra*, Convolvulaceae, etc.), accompanied by high amounts of *Pinus* and *Botryococcus* are very abundant alternate with a vegetation dominated by mesothermic–riparian (*Carya*, *Zelkova*, *Celtis*, *Salix*, etc.) and hygrophilous trees. During the later periods, *Pinus* and *Botryoccus* are very scarce (Fig. 6).

6. Spectral analysis

6.1. Methods

A spectral analysis of the pollen records has been performed for the upper lithological unit (interval 161–91 m) of the Rubielos de Mora-1 core. This unit is characterized by a very well developed oxic–anoxic cyclic sequence of greenish–greyish massive clays (oxic facies) and dark/brown laminated clays (anoxic facies). Fifty seven samples from this upper unit (interval 147.72–91 m) have been studied for pollen analysis (Fig. 6). As the samples are unevenly spaced, the Lomb–Scargle fourier transform (Press et al., 1992) algorithm has been used to estimate the power spectrum for such a data set. Spectral analysis was performed on a time series of 57 pollen data points, based on the relative abundance of two significant groups; thermophilous elements and mesothermic elements.

According to our preferred option-1 magnetostratigraphic correlation (Fig. 4A), the average sedimentation rate between reversal levels at 101.4 m (top C5Cn.3n) and 140.3 m (top C5Dn) is 5.6 cm/kyr. Option-2 (top C5ADn and top C5Bn.2n) results in average sedimentation rate of 4.6 cm/kyr and option-3 (top C6An.2n and top C6AAr.1n) in a rate of 4 cm/kyr (Fig. 4B).

Prior to the interpretation of the peaks, it is necessary to state that for the Miocene, the values of the main astronomical periods can be considered similar to those at present; for precession (P_1–P_2, 19 000–23 000 yr), obliquity (O_1–O_2, 41 000–54 000 yr) and eccentricity (E_1–E_2–E_3, 95 000–123 000 yr for short-term and 413 000 yr for long-term) (Berger et al., 1989; Berger et al., 1992).

6.2. Results

The spectral analysis results of the thermophilous (Fig. 7A) and mesothermic (Fig. 7B) elements reveal a defined cyclic pattern (Table 1). Although in some cases the significance level is relatively low, the power spectra of the two analyzed elements show some important similarities. The most obvious similarity is the presence of a common group of peaks, one of them above the 90% significance level (Fig. 7; Table 1); at 2.10 m in the

Table 1
Selected peaks in the spectral analysis of the relative abundance of (A) thermophilous and (B) mesothermic elements in the Rubielos de Mora-1 core

Peak	Frequency	Thickness (m)	Period (yr)	Interpretation
Thermophilous elements				
a	0.480	2.10	37.500 (opt. 1) 45.652 (opt. 2)	Obliquity
Mesothermic elements				
a	0.485	2.06	36.785 (opt. 1) 44.785 (opt. 2)	Obliquity

Periodicities are calculated taking into account the different sedimentary rates from Option 1 and 2, the two best correlations to the ATNTS04 (see text).

thermophilous and at 2.06 m in the mesothermic elements. Using the calculated sedimentation rates (for option 1 and 2, option 3 has been discarded, see above), this small-scale cyclicity has a periodicity of about 37.500–36.785 yr considering our preferred option, the option 1 (option 1 in Table 1; Fig. 4A), or about 45.652 – 44.782 yr for option 2 (option 2 in Table 1; Fig. 4A) and hence suggest a relation to the orbital obliquity cycle.

7. Discussion

7.1. Flora and vegetation: climatic implications

The pollen assemblages indicate a juxtaposition of strongly contrasting environments characterized by the presence of subdesertic taxa, typical for open and steppe environments (Quézel, 1965; White, 1983; Audru et al., 1987; Quézel and Médail, 2003) and conditioned by a long dry season, and riparian plants requiring a large amount of water (Wang, 1961). This contrast is explained by the significant availability of a water source on land around the Rubielos de Mora lake. This type of vegetation heterogeneity frequently occurs in subtropical and tropical Africa, as around Tanganyika Lake (Castroviejo, 2004), where water availability clearly controls vegetation and compensates for the lack of precipitation during the summer. Therefore, the over-represented riparian vegetation, only present around the Rubielos de Mora lake, was azonal. The vegetation which really characterized the area during the Early Miocene is considered subdesertic. This outcome agrees with previous data of macrofloras from the Vallès–Penedès basin where several subdesertic taxa of the family Caesalpiniaceae (*Banksia*, *Caesalpinia*, *Cassia*), Mimosaceae (*Acacia*, *Mimosa*) and Proteaceae (*Grevillea*, *Protea*) have been identified for the same time-span (Sanz de Siria Catalán, 1993).

During the Early Miocene, the European mid-latitudes were characterized by a subtropical climate. This is deduced by the low values of the isotopic data (Miller et al., 1991; Paul et al., 2000; Zachos et al., 2001; Billups and Schrag, 2002), paleobotanical studies (Bessedik, 1985; Sanz de Siria Catalán, 1993; Utescher et al., 2000; Roth-Nebelsick et al., 2004; Jiménez-Moreno, 2005; Jiménez-Moreno et al., 2005; Mosbrugger et al., 2005; Jiménez-Moreno, 2006), fossil mammals (Calvo et al., 1993) and is supported here by the abundance of thermophilous elements as can be seen in the pollen spectra (Fig. 6).

The presence of several xerophytes in the pollen spectra and in the macrofloras of close areas (Sanz de Siria Catalán, 1993) suggests that the climate was dry, characterized by a strong seasonality with periods lacking precipitation for perhaps 7–9 months (Sanz de Siria Catalán, 1993; this study). This inferred dry climate also agrees with previous climatic interpretations for the Early Miocene based on fossil mammals (Calvo et al., 1993). Therefore, our results point to warmer and drier climatic conditions than the previous paleobotanic studies carried out in the Rubielos de Mora Basin (Fernández Marrón and Álvarez-Ramis, 1988; Álvarez Ramis and Fernández Marrón, 1994; Barrón and Sansisteban, 1999; Roiron et al., 1999; Rubio et al., 2003). We assume that the over-representation of riparian plants in the pollen spectra and macrofloras is a plausible explanation for the wetter climatic interpretations and reconstructions in these studies.

Previous palynological studies have shown that subdesertic plants already existed in southwestern Europe and North Africa during the Late Miocene (Suc and Bessais, 1990; Chikhi, 1992; Bertini et al., 1998; Bachiri Taoufiq et al., 2001; Fauquette et al., 2006) and the Pliocene (Bessais and Cravatte, 1988; Suc, 1989; Suc et al., 1995). In this study we show that these taxa already occurred in the southern part of the northern Mediterranean area during at least the Early Miocene. Hence, prior to the late Miocene (Messinian) a Saharan type of climate already existed in southern Europe. Modern floras show that these subdesertic elements (i.e., *Acacia*, *Cassia* and *Nitraria*) grow in North Africa, including the Saharan Desert (Quézel, 1965). During the late Miocene and Pliocene most of these elements gradually shifted from northern Mediterranean areas towards the south. This shift was caused by a climatic cooling which coincided with the onset of the Atlantic climate system (Bessedik, 1985; Suc et al., 2004).

7.2. Cyclic changes and lake level variation

Repetitive vegetation changes corresponding to a metric scale cyclicity are likely related to the effects of periodic lake level oscillations on the vegetation and pollen sedimentation, which in turn are controlled by climatic changes (Fig. 6). We distinguish:

(1) High lake level (laminated mudstones): during these stages, the lake bottom was anoxic. The lake reached its maximum expansion allowing the mesothermic-riparian vegetal formation to flourish generating a dense forest along the lake margin. The distance of the pollen dispersion in lakes is very short (see Faegri and Iversen, 1989 and references therein) and, therefore, pollen grains

coming from beyond the lake area (in this case the open subdesertic vegetation and *Pinus* and indeterminable Pinaceae) were poorly recorded. Also, the pollen production of the riparian trees is usually very high (Faegri and Iversen, 1989), favouring the sedimentation of their pollen grains into the lake. During lake high-stands, rhythmites were deposited. They record short periodic alternation between dry and more humid climate conditions (Anadón et al., 1988a). During this stage, the *Botryococcus* colonies were generally scarce and developed under stress as a result of low oxygen levels. This can be deduced by the almost structureless shape of the colonies (Guy-Ohlson, 1992, 1998; Rodríguez Amenabar and Ottone, 2003).

(2) Low lake level (massive clays): increasing evaporation caused a lowering of lake level thereby reducing the riparian vegetation and its regional distribution (Fig. 6). In contrast, thermophilous–xerophylous plants from vegetation belts outside the lake area were better represented. This was strengthened, at the end of the low lake level, by sudden fluvial inputs thereby transporting large amounts of pollen grains from the "outside" such as *Pinus* and indeterminable Pinaceae and also large quantities of thermophilous and xerophilous elements into the lake. During lake-lowstands and fluvial inputs the waters were mixed and well oxygenated (Anadón et al., 1988b) and *Botryococcus* was generally enriched in these sediments (Fig. 6).

According to the spectral analysis results of the pollen data (Fig. 7; Table 1), the orbitally induced cyclicity pattern registered in the Rubielos de Mora basin shows significant similarities with cyclic patterns recognized in surrounding Neogene basins in the eastern Iberian Chain. Based on the analysis of abiotic features, the most common meter-scale sedimentary cycles have been related to precessional and obliquity climate variations (Krijgsman et al., 1999; Abdul Aziz et al., 2000; Abdul Aziz, 2001; Luzón et al., 2002; Abdul Aziz et al., 2003a, b; Abdul Aziz et al., 2004), and hence the occurrence of obliquity cycles in the pollen record of the Rubielos de Mora-1 core can be justified. It has been shown that the obliquity controlled climate and global glacial–interglacial cycles during the Miocene and Pliocene (Lourens et al., 1992; Zachos et al., 1997). In the Mediterranean marine realm, periods of increased precipitation are associated with sapropels (Lourens et al., 1992; Foucault and Mélières, 2000) and correspond to summer insolation maxima (Hilgen, 1991). Therefore, variations in summer insolation controlled precipitation and cold-warm cycles, having a very strong influence in the effective precipitation, lake levels and vegetation in Rubielos de Mora.

8. Conclusions

The pollen analysis of the core Rubielos de Mora-1 (Rubielos de Mora basin) allowed characterization of the vegetation and reconstruction of the regional climate during the Early Miocene in NE Spain.

The abundance of thermophilous elements and the presence of several xerophytes in the pollen spectra and in the macrofloras of close areas indicate that the climate was generally dry-subtropical.

The pollen assemblages denote the juxtaposition of greatly contrasted environments. The presence of thermophilous and subdesertic elements together with mesothermic–riparian taxa indicates a significant availability of water around the Rubielos de Mora Lake. This water availability clearly controlled the vegetation and compensated for the lack of precipitation during the dry summer.

The pollen analysis also permitted the distinction of repetitive changes in the vegetation characterized by the alternation of periods of thermophilous–xerophilous rich vegetation with periods dominated by the abundance of mesothermic–riparian plants. The metric-scale vegetational changes coincide with sedimentological changes and show that this cyclicity is most-likely related to climate.

Cyclostratigraphic analysis of the relative abundance of the thermophilous and mesothermic groups in the pollen record reveals the presence of different scales of cycles. Using the sedimentation rate derived from the magnetostratigraphic calibration to the ATNTS04, an astronomical forced origin related to obliquity is inferred for the pollen cycles in the Early Miocene deposits from the Rubielos de Mora basin. We conclude that astronomical forced climate change affected both the ecological and depositional environment. Changes in the ecological environment are represented by periodic changes in the distribution (expansion) of vegetation. Similarly, astronomically forced climate changes affected the depositional environment through the alternation of oxic (greenish–greyish massive mudstones) – anoxic (dark/brown laminated mudstones) lake water conditions.

Acknowledgments

Enrique Sanz Rubio kindly organized the sampling. G. J.-M. was funded by a PhD grant ("Junta de

Andalucía", Spain) and a co-supervised grant from the French Ministry of Universities. Jan Van Dam kindly helped with information about the small mammals of Rubielos de Mora basin. The authors are indebted to the EEDEN Programme (ESF) for the invitation to participate in several international workshops. The authors would also like to thank Jodi Eckart for correcting the English. This paper benefited from the reviews from the editor and two anonymous reviewers.

References

Abdul Aziz, H., 2001. Astronomical forcing in continental sediments. (An integrated study of Miocene deposits from the Calatayud and Teruel basins, NE Spain). Geol. Ultraiectina, vol. 207. Utrecht, The Netherlands.

Abdul Aziz, H., Hilgen, F., Krijgsman, W., Sanz, E., Calvo, J.P., 2000. Astronomical forcing of sedimentary cycles in the middle to late Miocene continental Calatayud Basin (NE Spain). Earth and Planetary Science Letters 177, 9–22.

Abdul Aziz, H., Sanz-Rubio, E., Calvo, J.P., Hilgen, F., Krijgsman, W., 2003a. Palaeoenvironmental reconstruction of a middle Miocene alluvial fan to cyclic shallow lacustrine depositional system in the Calatayud Basin (NE Spain). Sedimentology 50, 211–236.

Abdul Aziz, H., Krijgsman, W., Hilgen, F., Wilson, D.S., Calvo, J.P., 2003b. An astronomical polarity timescale for the late middle Miocene based on cyclic continental sequences. Journal of Geophysical Research 108 (B3), 2159. doi:10.1029/2002JB001818.

Abdul Aziz, H., van Dam, J., Hilgen, F., Krijgsman, W., 2004. Astronomical forcing in Upper Miocene continental sequences: implications for the Geomagnetic Polarity Time Scale. Earth and Planetary Science Letters 222, 243–258.

Álvarez Ramis, C., Fernández Marrón, T., 1994. Conexiones establecidas entre los palinomorfos y los macrorestos vegetales del Mioceno medio de Rubielos de Mora (Teruel). In: Ramos, I.L.S. (Ed.), VIII Simposio de Palinología (A.P.L.E.). Polen y Esporas contribución a su conocimiento, Tenerife, Spain, pp. 323–331.

Alvarez Sierra, M.A., 1987. Estudio sistemático y bioestratigráfico de los Eomyidae (Rodentia, Mammalia) del Oligoceno superior y Mioceno inferior español. Scripta Geologica 86, 1–207.

Anadón, P., Cabrera, L., Julia, R., 1988a. Anoxic–oxic cyclical lacustrine sedimentation in the Miocene Rubielos de Mora Basin, Spain. In: Fleet, A.J., Kelts, K., Talbot, M.R. (Eds.), Lacustrine Petroleum Source Rocks. Geological Society Special Publication, vol. 40, pp. 353–367.

Anadón, P., Cabrera, L., Inglés, M., Julia, R., Marzo, M., 1988b. The Miocene lacustrine basin of Rubielos de Mora. Excursion guidebook of the international workshop on lacustrine facies models in rift systems and related natural resources. International association of sedimentologist, Barcelona–Rubielos de Mora, pp. 1–32.

Anadón, P., Cabrera, L., Julia, R., Roca, E., Rosell, L., 1989. Lacustrine oil-shale basins in Tertiary grabens from NE Spain (Western European Rift System). Palaeogeography, Palaeoclimatology, Palaeoecology 70, 7–28.

Anadón, P., Cabrera, Ll., Julià, R., Marzo, M., 1991. Sequential arrangement and asymmetrical fill in the Miocene Rubielos de Mora Basin (northeast Spain). In: Anadón, P., Cabrera, Ll., Kelts, K. (Eds.), Lacustrine Facies Analysis. Spec. Publ. Int. Ass. Sediment, vol. 13, pp. 257–275.

Audru, J., Cesar, G., Forgiarini, G., Lebrun, J., 1987. La végétation et les potentialités pastorales de la République de Djibouti. Institut d´Elevage et de Médecine Véterinaire des Pays Tropicaux, Maisons Alforts, France. 384 pp.

Bachiri Taoufiq, N., Barhoun, N., Suc, J.-P., Meon, H., Elaouad, Z., Benbouziane, A., 2001. Environment, végétation et climat du Messinien au Maroc. Paleontologia i Evolució 32–33, 127–138.

Barrón, E., Sansisteban, C., 1999. Estudio palinológico de la cuenca miocena de Rubielos de Mora (Teruel, España). Aspectos paleoecológicos y paleobiogeográficos. Boletín Real Sociedad Española Historia Natural (Sección Geología), vol. 95, pp. 67–82.

Berger, A., Loutre, M.F., Dehant, V., 1989. Milankovitch frequencies for pre-Quaternary. Nature 342, 133.

Berger, A., Loutre, M.F., Laskar, J., 1992. Stability of the astronomical frequencies over the Earth's history for paleoclimate studies. Science 255, 560–566.

Bertini, A., 2001. Pliocene climatic cycles and altitudinal forest development from 2.7 Ma in the Northern Apennines (Italy): evidence from the pollen record of the Stirone section (∼5. 1 to ∼ 2.2 Ma). Géobios 34 (3), 253–265.

Bertini, A., Londeix, L., Maniscalco, R., Di Stefano, A., Suc, J.-P., Clauzon, G., Gautier, F., Grasso, M., 1998. Paleobiological evidence of depositional conditions in the Salt Member, Gessoso-Solfifera Formation (Messinian, Upper Miocene) of Sicily. Micropalentology 44, 413–433.

Bessais, E., Cravatte, J., 1988. Les Écosystèmes Végéteux Pliocènes de Catalogne Méridionale. Variations Latitudinales dans le Domaine Nord-Ouest méditerranéen. Géobios 21, 49–63.

Bessedik, M., 1985. Reconstitution des environements Miocenes des regions nord-ouest Mediterraneennes à partir de la palynologie. Ph.D. Thesis, University of Montpellier 2, France.

Billups, K., Schrag, D.P., 2002. Palaeotemperatures and ice volume of the past 27 Myr revisited with paired Mg/Ca and $^{18}O/^{16}O$ measurements on benthic foraminifera. Paleoceanography 17, 1–11.

Calvo, J.P., Daams, R., Morales, J., López-Martínez, N., Agustí, J., Anadón, P., Armenteros, I., Cabrera, L., Civis, J., Corrochano, A., Díaz-Molina, M., Elizaga, E., Hoyos, M., Martín-Suarez, E., Martínez, J., Moissenet, E., Muñoz, A., Pérez-García, A., Pérez-Gonzalez, A., Portero, J.M., Robles, F., Sansisteban, C., Torres, T., Van der Meulen, A.J., Vera, J.A., Mein, P., 1993. Up-to-date Spanish continental Neogene síntesis and paleoclimatic interpretation. Revista de la Sociedad Geológica de España 6, 29–40.

Cande, S.C., Kent, D.V., 1995. Revised calibration of the geomagnetic polarity time scale for the late Cretaceous and Cenozoic. Journal of Geophysical Research 100, 6093–6095.

Castroviejo, S., 2004. Una visita a Gombe (Tanzania). Historia Natural 4, 34–45.

Chikhi, H., 1992. Une palynoflore méditerranéenne à subtropicale au Messinien pré-evaporitique en Algérie. Géologie Méditerranéenne 19, 19–30.

Cour, P., 1974. Nouvelles techniques de détection des flux et des retombées polliniques: étude de la sédimentation des pollens et des spores à la surface du sol. Pollen et Spores 16, 103–141.

Combourieu-Nebout, N., Vergnaud-Grazzini, C., 1991. Late Pliocene Northern Hemisphere glaciation: the continental and marine responses in the central Mediterranean. Quaternary Science Reviews 10, 319–334.

Crusafont-Pairó, M., Gautier, F., Ginsburg, L., 1966. Mise en évidence du Vindobonien inférieur continental dans l´Est de la province de Teruel (Espagne). Compte Rendu Sommaire des Sciences de la Societé Geologique de France 1, 30–32.

de Bruijn, H., Moltzer, J.G., 1974. The rodents from Rubielos de Mora; the first evidence of the existence of different biotopes in the Early Miocene of eastern Spain. Proceedings van de Koninklijke Akademie van Wetenschappen, Series B 77, 129–145.

de Bruijn, H., Daams, R., Daxner-Höck, G., Fahlbusch, V., Ginsburg, L., Mein, P., Morales, J., Heinzmann, E., Mayhew, D.F., van der Meulen, A.J., Schmidt-Kittler, N., Telles Antunes, M., 1992. Report of the RCMNS working group on fossil mammals, Reisensburg 1990. Newsletters on Stratigraphy 26 (2/3), 65–118.

Faegri, K., Iversen, J., 1989. Textbook of pollen analysis, IV Edition. J. Wiley & Sons, New York.

Fauquette, S., Suc, J.-P., Bertini, A., Popescu, S.-M., Warny, S., Bachiri Taoufiq, N., Perez Villa, M.J., Ferrier, J., Chikhi, H., Subally, D., Feddi, N., Clauzon, G., 2006. How much the climate forced the Messinian salinity crisis? Quantified climatic conditions from pollen. Palaeogeography, Palaeoclimatology, Palaeoecology 238, 281–301.

Fernández Marrón, T., Álvarez-Ramis, C., 1988. Note préliminaire sur l´étude paléobotanique du gisement de Rubielos de Mora (Teruel, Espagne). Résumé Séminaire de Paléobotanique, Lille, OFP Informations 9, 14.

Foucault, A., Mélières, F., 2000. Palaeoclimatic cyclicity in central Mediterranean Pliocene sediments: the mineralogical signal. Palaeogeography, Palaeoclimatology, Palaeoecology 158, 311–323.

Guy-Ohlson, D., 1992. *Botryococcus* as an aid in the interpretation of palaeoenvironment and depositional processes. Review of Palaeobotany and Palynology 71, 1–15.

Guy-Ohlson, D., 1998. The use of the microalga *Botryococcus* in the interpretation of lacustrine environments at the Jurassic–Cretaceous transition in Sweden. Palaeogeography, Palaeoclimatology, Palaeoecology 140, 347–356.

Hilgen, F.J., 1991. Extension of the astronomically calibrated (polarity) time scale to the Miocene/Pliocene boundary. Earth and Planetary Science Letters 107, 349–368.

Jiménez-Moreno, 2005. Utilización del análisis polínico para la reconstrucción de la vegetación, clima y estimación de paleoaltitudes a lo largo del arco alpino europeo durante el Mioceno (21–8 Ma), Ph.D. dissertation, Granada (Spain) and Lyon (France) 313 pp.

Jiménez-Moreno, 2006. Progressive substitution of a subtropical forest for a temperate one during the middle Miocene climate cooling in Central Europe according to palynological data from cores Tengelic-2 and Hidas-53 (Pannonian Basin, Hungary). Review of Palaeobotany and Palynology 142, 1–14.

Jiménez-Moreno, G., Rodríguez-Tovar, F.-J., Pardo-Igúzquiza, E., Fauquette, S., Suc, J.-P., Müller, P., 2005. High-resolution palynological analysis in late early–middle Miocene core from the Pannonian Basin, Hungary. Climatic changes, astronomical forcing and eustatic fluctuations in the Central Paratethys. Palaeogeography, Palaeoclimatology, Palaeoecology 216, 73–97.

Kirschvink, K., 1980. The least squares lines and plane analysis of paleomagnetic data. Geophysical Journal of the Royal Astronomical Society 62, 699–718.

Kloosterboer-van Hoeve, M.L., Steenbrink, J., Visscher, H., Brinkhuis, H., 2006. Millennial-scale climatic cycles in the Early Pliocene pollen record of Ptolemais, northern Greece. Palaeogeography, Palaeoclimatology, Palaeoecology 229, 321–334.

Krijgsman, W., Delahaije, W., Langereis, C.G., de Boer, P.L., 1999. Paleomagnetism and astronomically induced cyclicity of the Armantes section; a Miocene continental red bed sequence in the Calatayud–Daroca basin (Central Spain). Acta Geologica Hispanica 32, 201–219.

Larrasoaña, J.C., Murelaga, X., Garcés, M., 2006. Magnetobiochronology of Lower Miocene (Ramblian) continental sediments from the Tudela Formation (western Ebro basin, Spain). Earth and Planetary Science Letters 243, 409–423.

López-Martínez, N., 1989. Revisión sistemática y bioestratigráfica de los *Lagomorpha* (*Mammalia*) del Terciario y Cuaternario de España. Memorias del Museo paleontológico de la Universidad de Zaragoza, vol. 3. 342 pp.

Lourens, L.J., Hilgen, F.J., Gudjonsson, L., Zachariasse, W.J., 1992. Late Pliocene to Early Pleistocene astronomically forced sea surface productivity and temperature variations in the Mediterranean. Marine Micropaleontology 19, 49–78.

Lourens, L.J., Hilgen, F.J., Laskar, J., Shackleton, N.J., Wilson, D., 2004. The Neogene Period. In: Gradstein, F.M., Ogg, J.G., Smith, A.G. (Eds.), Geologic Time Scale 2004. Cambridge Univ Press, Cambridge, pp. 409–440.

Luzón, A., González, A., Muñoz, A., Sánchez-Valverde, B., 2002. Upper Oligocene–Lower Miocene shallowing-upward lacustrine sequences controlled by periodic and non-periodic processes (Ebro Basin, northeastern Spain). Journal of Paleolimnology 28, 441–456.

Martínez-Delclòs, X., Peñalver, E., Belinchón, M., 1991. Primeras aportaciones al estudio de los insectos del Mioceno de Rubielos de Mora, Teruel (España). Revista Española de Paleontología, N° Extraordinario 215–224.

Miller, K.G., Feigenson, M.D., Wright, J.D., Clement, B.M., 1991. Miocene isotope reference section, DSDP Site 608: an evaluation of isotope and biostratigraphic resolution. Paleoceanography 6, 33–52.

Montoya, P., 2002. Los yacimientos de vertebrados de Rubielos de Mora 2 y Alto Ballester (Mioceno Inferior, Rubielos de Mora). El patrimonio Paleontológico de Teruel, IET, pp. 295–304.

Montoya, P., Peñalver, E., Ruiz-Sánchez, F.J., Sansisteban, C. de, Alcalá, L., Belinchón, M., Lacomba, J.I., 1996. Los yacimientos paleontológicos de la cuenca terciaria continental de Rubielos de Mora (Aragón). Revista Española de Paleontología, N° Extraordinario 215–224.

Mosbrugger, V., Utescher, T., Dilcher, D.L., 2005. Cenozoic continental climatic evolution of Central Europe. PNAS 102 (42), 14964–14969.

Nix, H., 1982. Environmental determinants of biogeography and evolution in Terra Australis. In: Barker, W.R., Greenslade, P.J.M. (Eds.), Evolution of the flora and fauna of arid Australia. Peacock Publishing, Frewville, pp. 47–66.

Paul, H.A., Zachos, J.C., Flower, B.P., Tripati, A., 2000. Orbitally induced climate and geochemical variability across the Oligocene/Miocene boundary. Paleoceanography 15, 471–485.

Peñalver, E., Martínez-Delclòs, X., 2003. Insects in the gut content of immature amphibians (family Salamandridae): an exceptional preservation in the lower Miocene of Rubielos de Mora Basin (Teruel, Spain). European Palaeontological Association-Workshop "Exceptional Preservation", Teruel, Spain, pp. 79–80.

Peñalver, E., Martínez Delclòs, X., Barrón, E., 2002. Importancia patrimonial y propuesta de gestón del *Konservat-Lagerstätte* mioceno de Rubielos de Mora. El patrimonio Paleontológica de Teruel, IET, pp. 209–225.

Popescu, S.-M., 2001. Repetitive changes in Early Pliocene vegetation revealed by high-resolution pollen analysis: revised cyclostratigraphy of southwestern Romania. Review of Palaeobotany and Palynology 120, 181–202.

Popescu, S.-M., Suc, J.-P., Loutre, M.-F., 2006. Early Pliocene vegetation changes forced by eccentricity-precession. Example from Southwestern Romania, Palaeogeogr., Palaeoclimatol. Palaeoecol., vol. 238, pp. 340–348.

Press, W.H., Teukolsky, S.A., Wettlerling, W.T., Flannery, B.P., 1992. Numerical Recipes in C: The art of scientific computing, second ed. Cambridge University Press, Cambridge.

Quézel, P., 1965. La végétation du Sahara, du Chad à la Mauritanie. G. Fischer, Stuttgart.

Quézel, P., Médail, F., 2003. Ecologie et biogéographie des forêts du bassin méditerranéen. Elsevier, France.

Rodríguez Amenabar, C., Ottone, E.G., 2003. La aplicación de *Botryococcus* (Chlorococcales) como indicador paleoambiental en el Triásico de Argentina. Revista Española de Micropaleontología 35, 161–169.

Roiron, P., Ferrer, J., Liñan, E., Rubio, C., Díez, J.-B., Popescu, S., Suc, J.-P., 1999. Les flores du bassin lacustre de Rubielos de Mora. Nouvelles données sur les conditions climatiques au Miocène inférieur dans la région de Teruel (Espagne). Comptes Rendus de l´Académie des Sciences-Series IIA-Earth and Planetary Science 329, 897–904.

Roth-Nebelsick, A., Utescher, T., Mosbrugger, V., Diester-Haass, L., Walther, H., 2004. Changes in atmospheric CO_2 concentrations and climate from the Late Eocene to Early Miocene: palaeobotanical reconstruction based on fossil floras from Saxony, Germany. Palaeogeography, Palaeoclimatology, Palaeoecology 205, 43–67.

Rubio, C., Roiron, P., Ferrer, J., Díez, J.B., Popescu, S., Suc, J.-P., 2003. Paleobotanical and paleoecological data from Lower–Middle Miocene (Burdigalian) basin of Rubielos de Mora. European Palaeontological Association-Workshop "Exceptional Preservation", Teruel, Spain, p. 87.

Sanz de Siria Catalán, A., 1993. Datos sobre la paleoclimatología y paleoecología del Neógeno del Vallès-Penedès según las macrofloras halladas en la cuenca y zonas próximas. Paleontologia i Evolució 26–27, 281–289.

Suc, J.-P., 1984. Origin and evolution of the Mediterranean vegetation and climate in Europe. Nature 307, 429–432.

Suc, J.-P., 1989. Distribution latitudinale et étagement des asociations végétales au Cenozoique superieur dans l´aire ouest-mediterranénne. Bulletin Société Géologique de France 8, 541–550.

Suc, J.-P., Bessais, E., 1990. Pérennité d´un climat thermo-xérique en Sicile avant, pendant et après la crise de salinité messiniense. Comptes Rendus de l´Academie des Sciences Paris 310, 1701–1707.

Suc, J.-P., Diniz, F., Leroy, S., Poumot, C., Bertini, A., Dupont, L., Clet, M., Bessais, E., Zheng, Z., Fauquette, S., Ferrier, J., 1995. Zanclean (~Brunssumian) to early Piacenzian (~early–middle Reuverian) climate from 4° to 54° north latitude (West Africa, West Europe and West Mediterranean areas). Mededelingen Rijks Geologische Dienst 52, 43–56.

Suc, J.-P., Fauquette, S., Popescu, S.-M., 2004. L'investigation palynologique du Cénozoïque passe par les herbiers. Actes du Colloque "Les herbiers: un outil d'avenir. Tradition et modernité", Villeurbanne. Association Française pour la Conservation des Espèces Végétales, Nancy, pp. 67–87.

Utescher, T., Mosbrugger, V., Ashraf, A., 2000. Terrestrial climate evolution in Northwest Germany over the last 25 million years. Palaios 15, 430–449.

Wang, C.W., 1961. The forests of China with a survey of grassland and desert vegetation. Maria Moors Cabot Foundation. Harvard University, Cambridge, Massachusetts.

White, F., 1983. The vegetation of Africa, a decriptive memoire to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa. Natural Resources Research, vol. 20. UNESCO, Paris, France.

Zachos, J.C., Flower, B.P., Paul, H., 1997. Orbitally paced climate oscillations across the Oligocene–Miocene boundary. Nature 388, 567–570.

Zachos, J.C., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present. Science 292, 686–693.