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Repetitive changes in Early Pliocene vegetation revealed by high-resolution pollen analysis: revised cyclostratigraphy of southwestern Romania

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Abstract

A high-resolution pollen analysis has been carried out on the Lupoaia section (SW Romania) in order to check whether the repetitive clay–lignite alternations correspond to cyclic changes in climate. Increases in altitudinal tree pollen content appear to have been caused by drops in temperature, while developments of thermophilous elements correspond to rises in temperature, still under humid conditions. Such repeated changes in vegetation, on the whole consistent with the clay–lignite alternations, have been forced by cycles in eccentricity. On the basis of a comparison between the Lupoaia pollen record and (1) European climatostratigraphy (based on reference pollen diagrams documenting global changes), and (2) global climatic curves (eccentricity, $\delta^{18}O$), the age of the section has been reconsidered. The Lupoaia section (i.e. from lignite IV to lignite XIII) starts just before the C3n.3n Chron and probably ends just before the C3n.1n Chron. The section represents a time span of about 600 kyr, i.e. from about 4.90 Ma to about 4.30 Ma. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: pollen analysis; vegetation; cyclostratigraphy; Pliocene; Romania

1. Introduction

During the last decades, palynological efforts have been made to obtain a good knowledge of the European and Mediterranean Pliocene vegetation and climate (Zagwijn, 1960; Menke, 1975; Diniz, 1984; Suc, 1984a; Zheng and Cravatte, 1986; Drivaliari, 1993; Bertini, 1994). Today, reconstructions of vegetation and climate are coherent for North-European to Mediterranean latitudes during the whole Pliocene, more especially the Early Pliocene (i.e. the Zanclean stage from 5.32 to 3.6 Ma) (Suc and Zagwijn, 1983; Suc et al., 1995). In addition, a climate transfer function, based on pollen records, has been introduced, which underlines subtropical temperatures in southwestern Europe during the Early Pliocene (for example, 16.5°C as mean annual temperature in the Nice area) (Fauquette et al., 1999a).

Early Pliocene pollen data show consistent vegetation changes in Europe from north (Zagwijn, 1960; Menke, 1975) to south (Suc, 1984a; Bertini, 1994; Zheng and Cravatte, 1986), as well as from west (Diniz, 1984) to east (Drivaliari et al., 1999),

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that allow the subdivision of the period into three main climatic phases. Two main warm phases (Brunssumian A and C of Zagwijn (1960), pollen zones P Ia and P Ic of Suc (1984a)) encompass the first relative cooling episode (Brunssumian B of Zagwijn (1960), pollen zone P Ib of Suc (1984a)). This subdivision is in accordance with the large variations observed in the $\delta^{18}O$ curve from the ocean record (Tiedemann et al., 1994; Shackleton et al., 1995). Most of the European reference pollen diagrams include secondary fluctuations within the above mentioned climatic phases of the Early Pliocene (Susteren in The Netherlands: Zagwijn, 1960; Oldenswort 9 in Germany: Menke, 1975; Garraf 1 in the north-western Mediterranean shelf off-shore Spain: Suc and Cravatte, 1982; Rio Maior F 14 in Portugal: Diniz, 1984). Unfortunately, these pollen records have been established on a somewhat low number of samples, that do not allow accurate correlation with the continuous $\delta^{18}O$ record, and therefore with the astronomic parameters.

Van der Zwaan and Gudjonsson (1986) have established the first $\delta^{18}O$ record at a relative high-resolution for the Pliocene of Sicily which shows many fluctuations. More recently, Tiedemann et al. (1994) and Shackleton et al. (1995) have demonstrated that such $\delta^{18}O$ fluctuations are astronomically forced by precession (ca. 20-kyr cycles). In addition, Hilgen (1990, 1991a,b) has established a very accurate time scale for the Mediterranean Lower Pliocene based both on magnetostratigraphy and sedimentological cyclostratigraphy. It was demonstrated that rapid changes in sedimentation were simultaneously forced by precession and eccentricity (100- and 400-kyr cycles).

Certain long, continuous and very propitious land sections can provide high-resolution pollen records that may reveal whether the changes in vegetation are induced by astronomic cycles. The pollen records from Stirone and Monticino (Lower Zanclean of the Po Valley) suggest, despite a low sampling resolution, cyclic variations in the vegetation that are forced by eccentricity (Bertini, 1994). The Lupoaia section (southwestern Romania; Fig. 1) offers a long Early Pliocene sedimentary record, characterised by almost regular clay–lignite alternations which have been linked to eccentricity forcing (Van Vugt et al.,

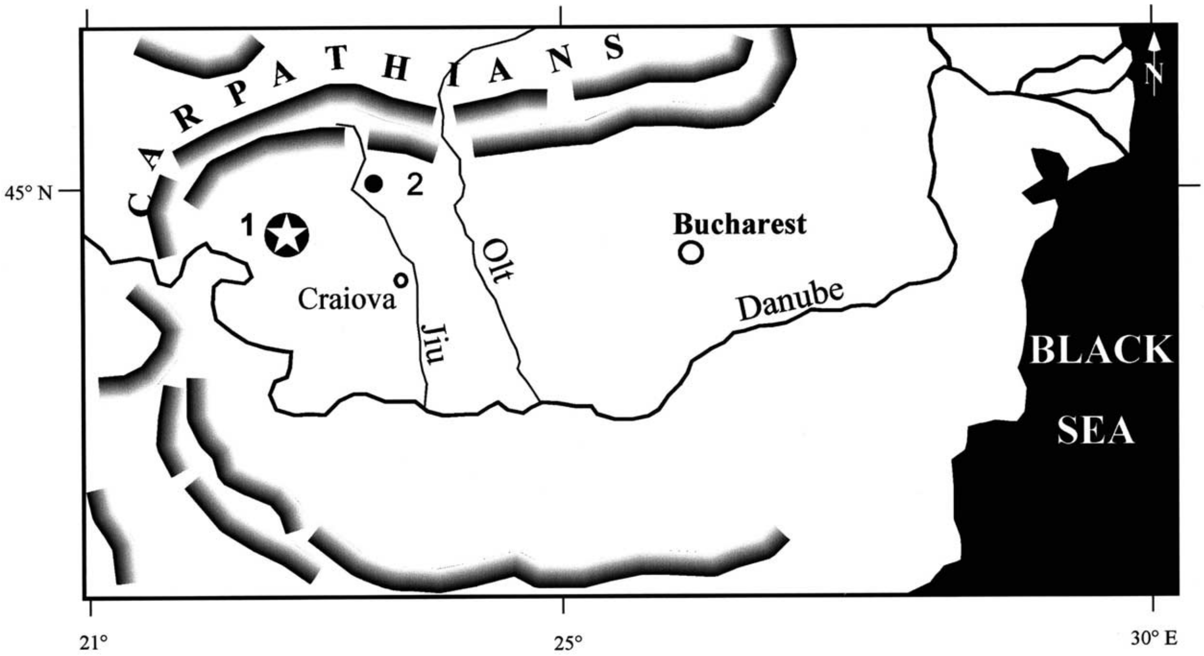


Fig. 1. Location of the Lupoaia section in the Dacic Basin. (1) Lupoaia, (2) Ticleni borehole.

2001). However, Van Vugt et al. (1998) have demonstrated that the lignite–clay alternations of the Early Pliocene Ptolemais lacustrine basin (northwestern Greece) were forced by precession: these lignites would correspond to drier phases and clays to moister phases (Kloosterboer-van Hoeve, 2000).

Accordingly, a high-resolution pollen investigation was carried out on the Lupoaia long section in order (1) to know whether Early Pliocene vegetation changes are related to astronomical cycles, and (2) to contribute to the clarification of the climatic significance of lignites located in the eastern Mediterranean region.

2. The Lupoaia section

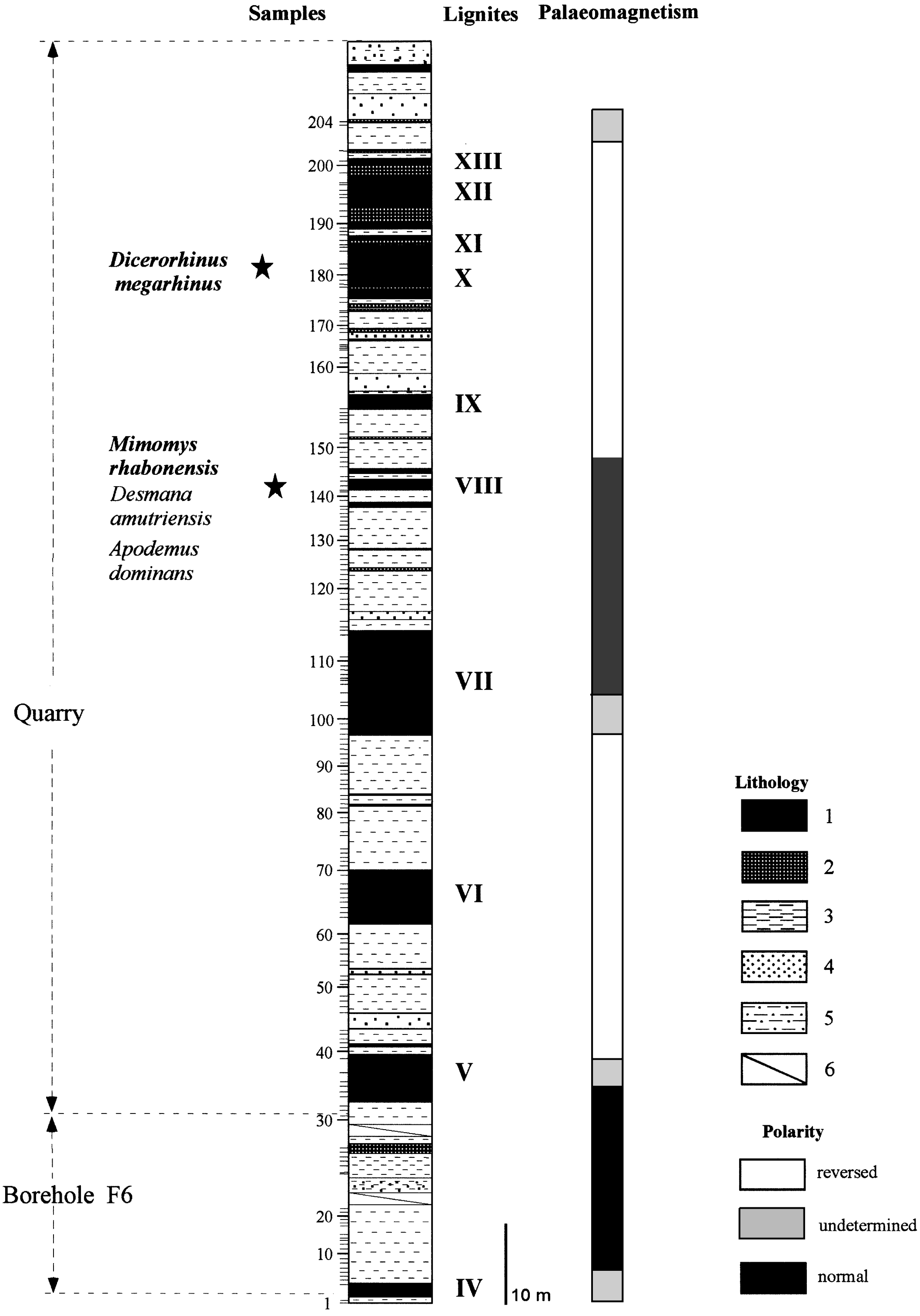
2.1. General characters

The Lupoaia quarry is located near the city of Motru (district of Gorj, Romania) close to the Carpathians in Oltenia, some 30 km north of the Danube river (Fig. 1). The quarry is especially characterised by clay–lignite alternations, and includes several sand layers of various thickness. The sedimentary record toward the base of the series has been recovered by cored boreholes.

The Lupoaia quarry is 121.50 m high and shows nine major lignite beds corresponding to lignite V to lignite XIII in the regional nomenclature. Some of them have been subdivided into two or three secondary layers as lignites VIII and X (Fig. 2). The underlying sediments cored in boreholes F6 (thickness: 21.20 m) and F11 include the lower layer of lignite V and lignite IV. The present palynological study begins below lignite IV and finishes above lignite XIII (Fig. 2), corresponding to a thickness of 133.70 m. Some other thin lignite or lignitic clay layers have been recorded. Blue-grey clays are abundant in the section and rich in leaf prints (Ticleanu and Buliga, 1992; Ticleanu and Diaconita, 1997). Fluvial sands are mainly concentrated in the mid and the upper part of the section (Fig. 2). The thickness of the different layers varies within the Motru Basin; for example, sands are thicker in the south and the lignite beds contain more subdivisions towards the south-east. According to Ticleanu and Diaconita (1997), the Motru lignites belong to a deltaic system which, according to Clauzon and Suc (personal information), flowed into the Dacic Sea close to the Zanclean Danube delta, in the area of Dobreta Turnu Severin.

2.2. Chronology

Radan and Radan (1998) have performed palaeomagnetic measurements of samples from both the Lupoaia quarry (more than 1000 samples) and two cored boreholes F6 and F11 (about 380 samples). Two normal palaeomagnetic events were identified in the lowermost part (from clays overlying lignite IV to the upper lignite V) and in the mid-part of the section (from about lignite VII to lignite VIII; Fig. 2), respectively. The lower normal episode is preceded by a relatively prolonged undetermined polarity zone, while another one has been identified above lignite XIII (Fig. 2). Some other thin undetermined polarity zones occur along the section but they mostly correspond to lignites which do not constitute a very good lithology for palaeomagnetic measurements. Radan and Radan (1998) have considered these normal episodes to represent the C3n.2n Chron (i.e. the Nunivak Chron) and the C3n.1n Chron (i.e. the Cochiti Chron), respectively. To identify the two normal episodes, the authors used as biostratigraphic argument the presence within lignite VIII (Fig. 2) of a primitive *Mimomys* (*Mimomys rhabonensis*) considered to be representative of the lowermost mammal zone MN 15 (Radulescu et al., 1997). However, it is assumed that the primitive *Mimomys* have appeared in Romania at the same time as in the northwestern Mediterranean region, i.e. after the C3n.1n Chron (locality of Mas Soulet, Nîmes area) (Aguilar and Michaux, 1984; Aguilar et al., 1999). In other words, it is considered that the 'boundary' between mammal zones MN 14 and MN 15 is coeval in eastern Europe and western Europe, a concept that is currently topic of strong international discussion (ad hoc Working Group of the Regional Committee on the Mediterranean Neogene Stratigraphy). In northern Greece, the first *Mimomys* (*Mimomys davakosi*) is recorded in the Ptolemais 3 locality


Samples
Lignites
Palaeomagnetism
204
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
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1
XIII
XII
XI
X
IX
VIII
VII
VI
V
IV
Dicerorhinus megarhinus
Mimomys rhabonensis
Desmana amutriensis
Apodemus dominans
Quarry
Borehole F6
10 m
Lithology
1
2
3
4
5
6
Polarity
reversed
undetermined
normal

Fig. 2.

(Van de Weerd, 1978) that would belong to the C3n.3n Chron (Van Vugt et al., 1998) according to the stratigraphic information provided by Van de Weerd (1978), Koufos and Pavlides (1988) and Van Vugt et al. (1998). Magnetostratigraphy of the Ptolemais section suggests that *Mimomys* appeared earlier in eastern Europe than in western Europe. This view is also supported by the first appearance of the ancestor of *Mimomys*, *Promimomys insuliferus*, which, in the Ptolemais section (Kardia locality; Van de Weerd, 1978) would occur in a time span including the C3n.4n Chron (Van Vugt et al., 1998) according to the local stratigraphic information (Van de Weerd, 1978; Koufos and Pavlides, 1988; Van Vugt et al., 1998). As a consequence, there is no reliable argument provided by micromammals to support the chronological assignment of the Lupoaia section to the successive chrons C3n.2n and C3n.1n. Using a cryogenic magnetometer, Van Vugt et al. (2001) have confirmed the polarity reversals of the Lupoaia quarry (78 samples going from lignite V to lignite IX), including two relatively prolonged undetermined polarity zones (within and above lignite V, within lignite VII) (Fig. 2). The authors followed the same chronological interpretation; in their opinion, the reversed episode recorded in the upper part of the section could be assigned, considering its relatively important duration, to the long reversal C2Ar. Such an interpretation does not take into account possible changes in sedimentation rate in the uppermost part of the section, which is richer in lignite and sand beds.

Among the other micromammal remains found in the lignite bed VIII of the quarry, there is *Apodemus dominans*, which is a common species in the European Pliocene, and also found in the three mammal localities of Ptolemais (Van de Weerd, 1978).

Further information is provided by the discovery of *Dicerorhinus megarhinus* remains in the Horaşti mine (Motru Basin) lignite X (Apostol and Enache, 1979). According to Guérin (1980), this species corresponds to the Lower Pliocene (Mammal Zones 14 and 15). The size of the Horaşti mine specimen (Apostol and Enache, 1979) is almost similar to that from the specimen of Montpellier (De Serres, 1819). In western Europe, the range of the species should be comprised between about 5 and 4 Ma.

Therefore, mammal fauna does not provide an unquestionable chronological support to the proposed magnetostratigraphic assignment (Radan and Radan, 1998; Van Vugt et al., 2001); on the contrary, the data suggest an age older than that proposed for the Lupoaia section.

3. Materials and methods

Numerous samples (231) of clays and lignites have been analysed from the Lupoaia section. Most of them (204) have provided a rich pollen flora. Samples 1–31 come from the cored borehole F6, samples 32–204 come from the quarry (Fig. 2).

Clay samples have been prepared following the classic method (successive actions by HCl, HF, etc.; concentration of palynomorphs using $ZnCl_2$ at density = 2, then filtering at 10 µm). Another technical approach has been used for the lignites, starting with a KOH action which replaces the acids. Samples are mounted in glycerine to allow complete observation of palynomorphs, necessary for their proper botanical identification. More than 150 pollen grains (*Pinus*, a generally over-represented element in the pollen flora, excluded) have been counted per sample. Results are given in a simplified detailed pollen diagram where pollen percentages are calculated relative to the total pollen sum (Fig. 3). Spores (pteridophytes, bryophytes, fungi), algae and dinoflagellate cysts have been scored separately. Dry samples have been

Fig. 2. Lithological succession of the Lupoaia section (quarry and cored borehole F6) and its magnetostratigraphic subdivision (Radan and Radan, 1998; Van Vugt et al., 2001); stratigraphic locations of mammal remains are indicated. Lithology: (1) lignite; (2) lignitic clay; (3) clay; (4) sand; (5) sandy clay; (6) not recovered interval within borehole F6.

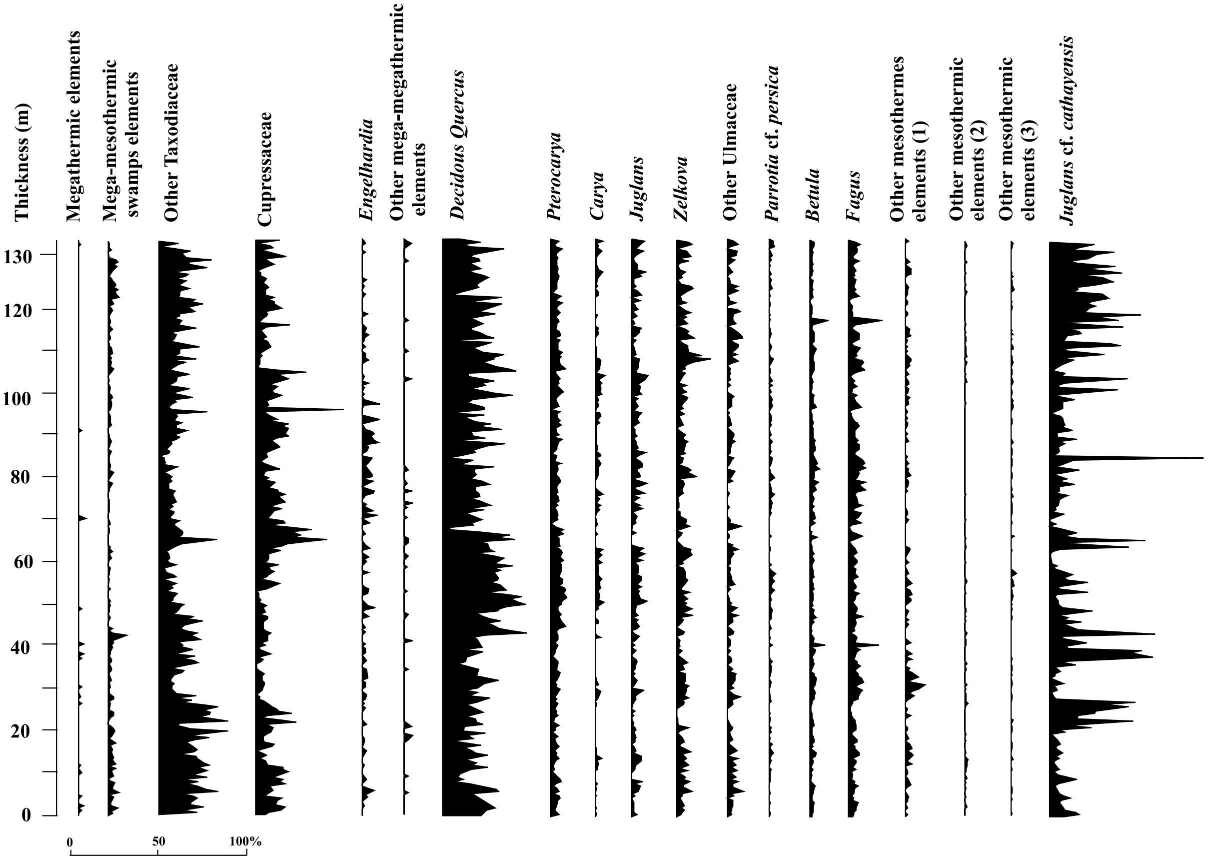

Fig. 3.

weighted, and volumes of residues after treatment were measured in order to calculate pollen concentrations using the method described by Cour (1974). A synthetic pollen diagram has been constructed according to the ecological requirements of taxa (Fig. 4). Such standard synthetic pollen diagrams (Suc, 1984a) clearly document temporal changes in pollen content, and aid in comparisons between pollen records throughout Europe and the Mediterranean region; they are generally used for detecting long-distance climatostratigraphic relationships (Suc et al., 1995).

Interpretations of the pollen records are also supported by statistical analyses (principle component analysis, spectral analysis).

Pollen and spore counts from the Lupoaia section are archived at the Laboratory 'PaléoEnvironnements et PaléobioSphère' (University Claude Bernard - Lyon 1) and will be available from the 'Cenozoic Pollen and Climatic values' database (CPC)[1].

4. Pollen flora and vegetation

The pollen flora is very rich (137 taxa; Fig. 3), and dominated by trees. These results considerably increase the known floristic palaeodiversity of the area (the delta environment to the altitudinal belts of the Carpathians), when compared to the preliminary palynological study of Petrescu et al. (1989), and the analyses of palaeobotanical macrofossils (Ticleanu, 1992; Ticleanu and Dia-

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[1] For further information, contact Dr. Séverine Fauquette (same address as the author), curator of the CPC database (severine.fauquette@univ-lyon1.fr).

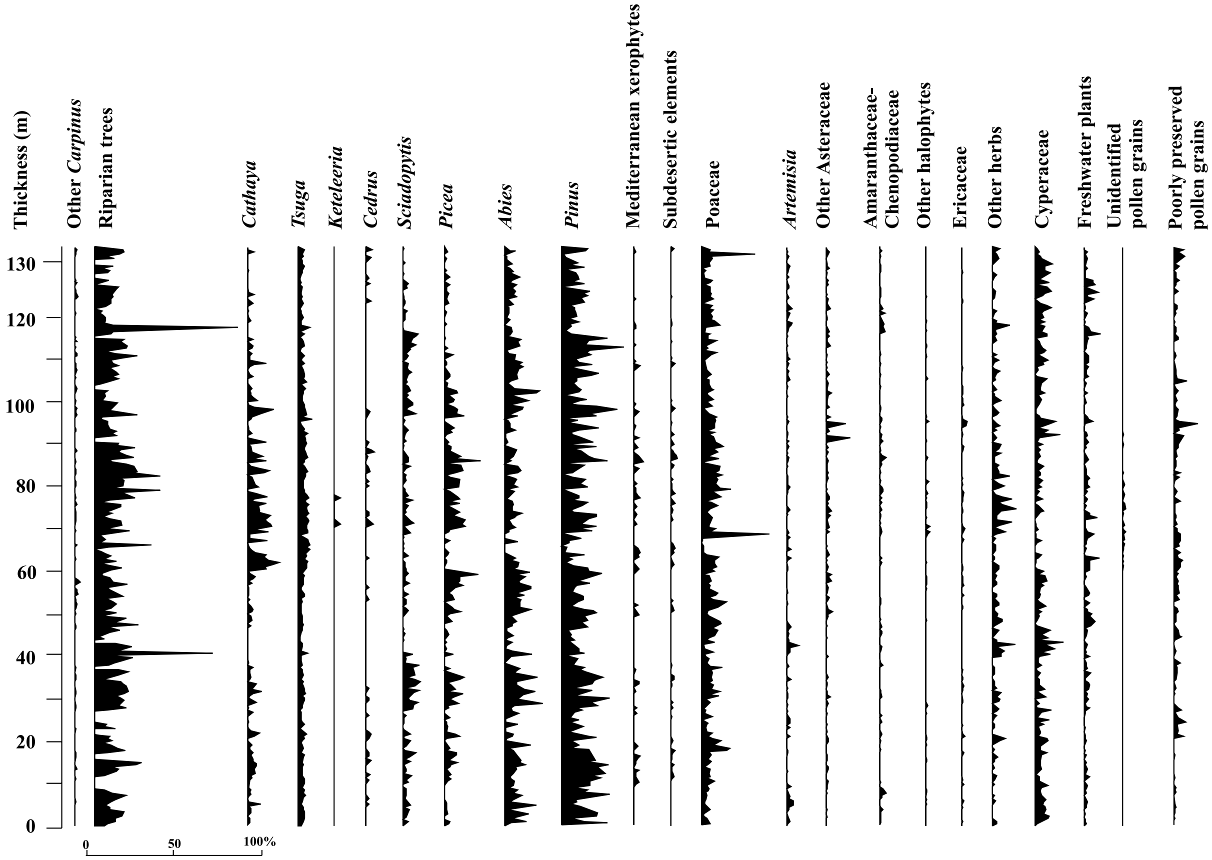
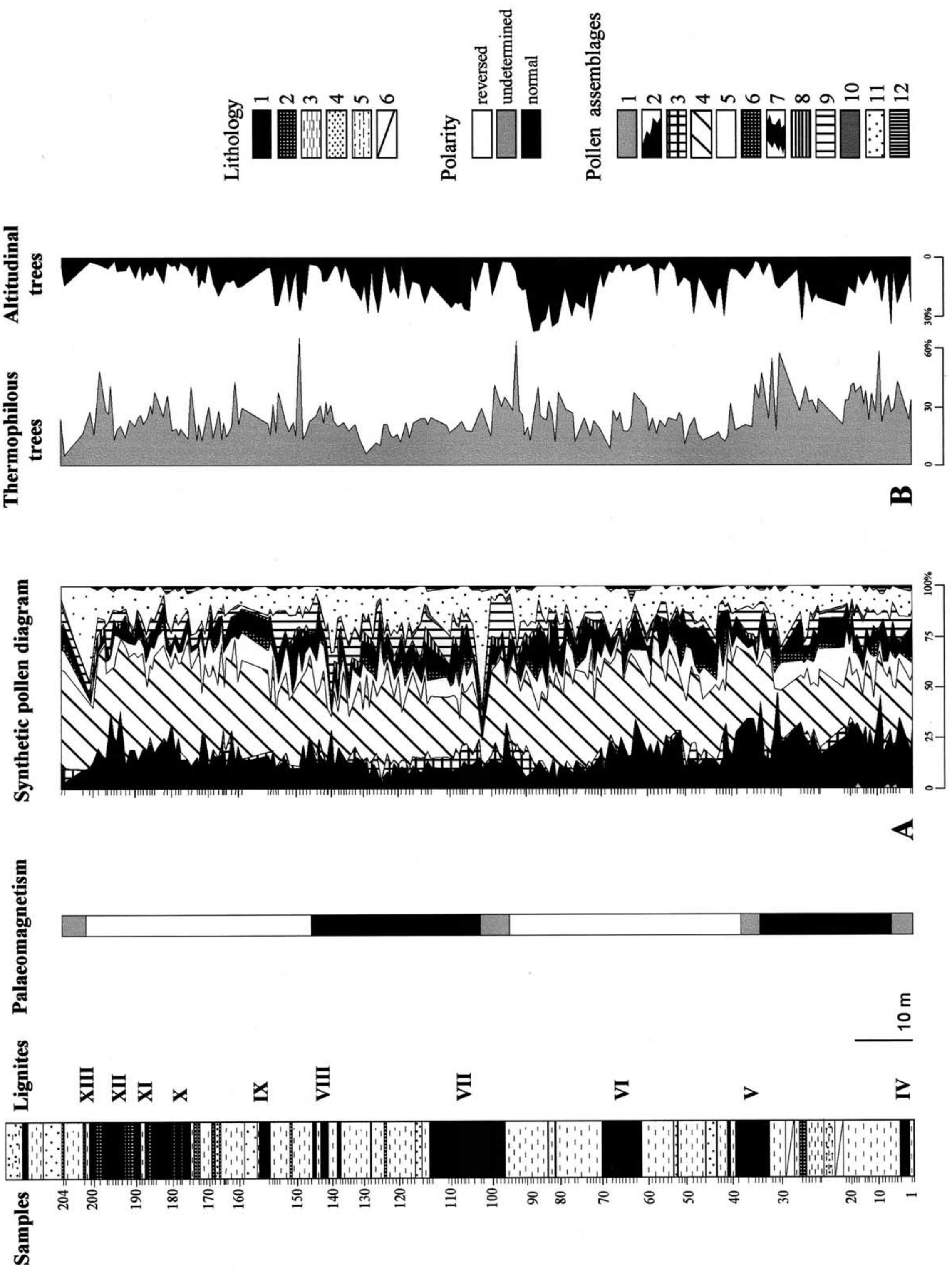


Fig. 3. Simplified detailed pollen diagram of the Lupoaia section. Some scarcely represented taxa are grouped into the following sections: (1) megathermic elements: Euphorbiaceae *p.p.*, *Amanoa*, Meliaceae, *Entada* type, other Mimosoideae, *Pachysandra* type, Sapindaceae, Loranthaceae, Tiliaceae *p.p.*; (2) mega-mesothermic swamp elements: Cyrillaceae–Clethraceae, *Myrica*, *Taxodium* type, *Cephalanthus*, *Nyssa* (*Nyssa* cf. *sinensis* and *Nyssa* cf. *aquatica*); (3) other Taxodiaceae: *Sequoia* type, non-identified Taxodiaceae; (4) other mega-mesothermic elements: Arecaceae, Sapotaceae, Anacardiaceae, Araliaceae, *Microtropis fallax*, *Distylium* cf. *sinensis*, *Parrotiopsis* cf. *jacquemontiana*, *Leea*, *Magnolia*; (5) other Ulmaceae: *Celtis*, *Ulmus*, *Ulmus–Zelkova* type; (6) other mesothermic elements (1): *Carpinus* cf. *orientalis*, *Platanus*, *Ostrya*, *Liquidambar* (including *Liquidambar* cf. *orinetalis*); (7) other mesothermic elements (2): *Vitis*, *Hedera* (including *Hedera* cf. *helix*), *Lonicera*, *Buxus sempervirens* type, *Ligustrum*; (8) other mesothermic elements (3): *Sambucus*, *Viburnum*, *Rhus*, *Tilia*, *Ilex*, *Acer*, *Tamarix*; (9) other *Carpinus*: *Carpinus* cf. *betulus*, non-identified *Carpinus*; (10) riparian trees: *Alnus*, *Salix*, *Populus*, *Fraxinus*; (11) Mediterranean xerophytes: *Olea*, *Phillyrea*, *Pistacia*, *Quercus ilex* type, *Cistus*, *Periploca*, *Phlomis* cf. *fruticosa*; (12) subdesertic elements: *Nolina*, *Prosopis*; (13) other Asteraceae: Asteroideae, Cichorioideae, *Centaurea*; (14) other halophytes: *Ephedra*, Caryophyllaceae, Plumbaginaceae; (15) other herbs: *Erodium*, *Convolvulus*, *Linum*, *Mercurialis*, *Euphorbia*, Brassicaceae, Apiaceae, *Scabiosa*, *Knautia*, Malvaceae, Borraginaceae, *Helianthemum*, *Plantago*, *Rumex*, *Polygonum* (including *Polygonum* cf. *aviculare* and *Polygonum* cf. *lapatifolium*), Rosaceae, *Asphodelus*, other Liliaceae, *Cannabis*, other Cannabaceae, Papillionideae; (16) freshwater plants: *Thalictrum*, other Ranunculaceae, *Butomus*, *Restio*, other Restionaceae, *Myriophyllum*, *Potamogeton*, *Sparganium*, *Typha*, *Nuphar*, *Nymphaea*, Oenotheraceae, *Trapa*, *Utricularia*, other Monocotyledones; (17) non-identified pollen grains include *Gymnocardiidites subrotunda* and *Tricolporopollenites sibiricum*. Percentages are calculated relative to the total pollen sum.

conita, 1997). In general, pollen concentration is relatively high (more than 1000 pollen grains/g of sediment), but shows important variations (from 50 up to 83 000 pollen grains/g of sediment).

The dominant taxa have been used to describe and interpret the detailed pollen diagrams in terms of the following vegetational units:

(1) Subtropical swamp forests with the Taxo-


Samples
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10
1
Lignites
XIII
XII
XI
X
IX
VIII
VII
VI
V
IV
10 m
Palaeomagnetism
A
Synthetic pollen diagram
0
25
50
75
100%
B
Thermophilous trees
0
30
60%
Altitudinal trees
0
30%
Lithology
1
2
3
4
5
6
Polarity
reversed
undetermined
normal
Pollen assemblages
1
2
3
4
5
6
7
8
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11
12

diaceae as main component, in which regular occurrences of *Taxodium* pollen-type are found, including *Taxodium* and *Glyptostrobus*. Today, *Taxodium distichum* is found in the coastal swamps of Northeastern America (Florida and Mississippi delta; George, 1972; Roberts, 1986), and *Glyptostrobus* grows in swampy lowlands within the evergreen broad-leaved forest in China (Wang, 1961). According to macrofossil evidence, the Taxodiaceae living in the Lupoaia Pliocene swamps belong to *Glyptostrobus* (*Glyptostrobus europaeus*; Ticleanu, 1992). Cupressaceae pollen grains are also abundant but cannot be identified more accurately. As their frequency trends resemble those of the Taxodiaceae, it is assumed that most Cupressaceae were represented by taxa requiring warm and humid conditions, such as those living today in subtropical Asia (*Chamaecyparis*). This is also supported by the position of Cupressaceae on the second axis of the principle component analysis (Fig. 5). Some other elements formed part of these associations, including *Cephalanthus*, *Myrica* or *Nyssa* cf. *sinensis*. In addition, these assemblages probably contained some subtropical to warm-temperate elements; *Salix p.p.*, *Alnus p.p.*, *Populus p.p.* and a *Juglans* species which is morphologically similar to *Juglans cathayensis*, were found among the plant macrofossils (Ticleanu, personal information). These elements may be the first indicators of the forthcoming warm-temperate swamps of the Middle-Late Pliocene (Drivaliari et al., 1999). Several pteridophytes including *Osmunda* were found in the swamp assemblages.

(2) The abundance of Cyperaceae pollen suggests the presence of herbaceous marshes (see the result of the principle component analysis; Fig. 5). Water plants were also present in such an environment (Restionaceae, *Myriophyllum*, *Potamogeton*, *Trapa*, *Typha*, *Sparganium*, *Nuphar*, Oenotheraceae). These two pollen assemblages have a strong resemblance to the modern vegetation of South Florida (George, 1972) and the Mississippi delta (Roberts, 1986), where swamp forests (with *Taxodium distichum*) and herbaceous marshes (with Cyperaceae mainly) coexist. Their respective floristic composition can also be seen in the modern surface pollen spectra (Rich, 1985; Suc, personal information). Their constitution is in agreement with macroflora (Ticleanu, 1992; Ticleanu and Diaconita, 1997).

(3) Behind such a coastal vegetation, and up to mid-altitude, a mixed subtropical to warm-temperate forest existed with mega-mesothermic and

Fig. 4. (A) Synthetic pollen diagram of the Lupoaia section. Pollen grains have been grouped according to ecological significance of the concerned plants. Lithology: see Fig. 2. Pollen assemblages: (1) megathermic elements (unidentified Euphorbiaceae, *Amanoa*, Mimosaceae including *Entada* and *Pachysandra* types, Meliaceae, Sapindaceae, Loranthaceae, Arecaceae, Sapotaceae, Tiliaceae); (2) mega-mesothermic elements (mainly Taxodiaceae, *Engelhardia*, *Cephalanthus*, *Distylium*, *Parrotiopsis jacquemontiana*, *Microtropis fallax*, Cyrillaceae–Clethraceae, *Leea*, *Myrica*, *Nyssa sinensis*, *Parthenocissus henryana*, *Ilex floribunda* type, Anacardiaceae, Araliaceae, *Magnolia*); (3) lower–mid-altitude coniferous elements, *Cathaya*; (4) mesothermic elements (deciduous *Quercus* chiefly, *Carya*, *Pterocarya*, *Liquidambar*, *Parrotia persica*, *Carpinus*, *Ulmus*, *Zelkova*, *Celtis*, *Ostrya*, *Platanus*, *Juglans*, *Juglans* cf. *cathayensis*, *Nyssa*, *Sciadopitys*, *Buxus sempervirens* type, *Acer*, *Tilia*, *Fagus*, *Alnus*, *Salix*, *Populus*, Ericaceae, *Vitis*, *Hedera*, *Lonicera*, *Fraxinus*, *Ligustrum*, *Sambucus*, *Viburnum*, *Rhus*, *Ilex*, *Tamarix*, *Betula*); (5) *Pinus*. Meso-microthermic trees: (6) mid-altitude trees, *Cedrus*, *Keteleeria* and *Tsuga*; (7) montane trees, *Abies* and *Picea*; (8) elements without significance (Rosaceae, Ranunculaceae, unidentified pollen grains, poorly preserved pollen grains); (9) Cupressaceae; (10) 'Mediterranean' xerophytes such as *Olea*, *Phillyrea*, *Quercus ilex* type, *Pistacia*, *Cistus*, *Phlomis* cf. *fruticosa*, *Periploca*. Herbs: (11) Cyperaceae, Poaceae, Asteraceae, *Plantago*, Brassicaceae, Apiaceae, *Polygonum*, *Rumex*, Amaranthaceae–Chenopodiaceae, Caryophyllaceae, *Linum*, *Erodium*, *Convolvulus*, *Mercurialis*, *Euphorbia*, *Scabiosa*, *Knautia*, Malvaceae, Borraginaceae, *Helianthemum*, *Asphodelus*, Liliaceae, Cannabaceae, Fabaceae, Plumbaginaceae, *Butomus*, water plants such as *Potamogeton*, Restionaceae, *Myriophyllum*, *Typha*, *Sparganium*, *Thalictrum*, *Nuphar*, *Nymphaea*, Oenotheraceae, *Trapa*, *Utricularia*; (12) steppe elements (*Artemisia*, *Ephedra*). (B) Record of thermophilous trees (i.e. the megathermic elements (such as Mimosaceae including *Proposis* and *Entada* type, *Pachysandra* type, Meliaceae, Euphorbiaceae including *Amanoa*, Sapindaceae, Loranthaceae, Tiliaceae, Arecaceae, Sapotaceae) and the mega-mesothermic elements such as Taxodiaceae (*Sciadopitys* excluded), *Juglans* cf. *cathayensis*, *Engelhardia*, *Myrica*, *Nyssa* cf. *sinensis*, *Distylium*, *Parthenocissus* cf. *henryana*, *Parrotiopsis* cf. *jacquemontiana*, *Microtropis fallax*, *Ilex floribunda* type, Cyrillaceae–Clethraceae, *Leea*, *Magnolia*, *Nolina*, plus Cupressaceae] in contrast to altitudinal trees (*Tsuga*, *Cedrus*, *Cathaya*, *Abies* and *Picea*) along the Lupoaia section.

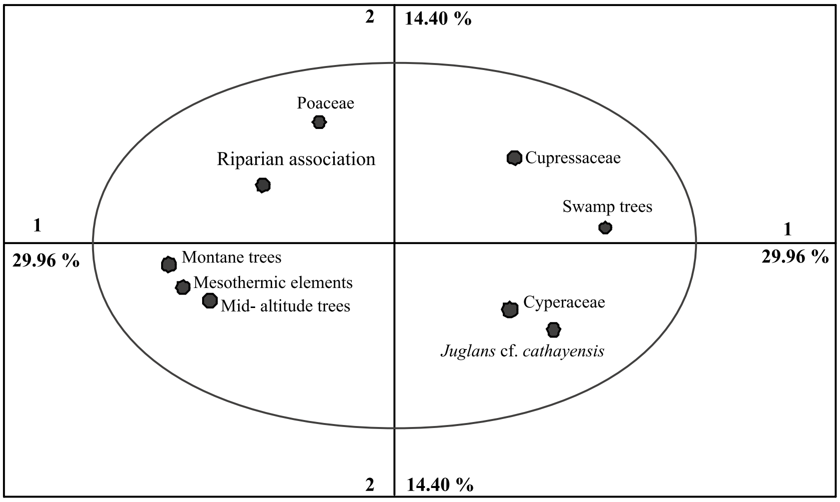


Fig. 5. Principle component analysis applied to some key taxa and some ecological groups recorded in the Lupoaia pollen analysis. Axis 1 does not show any clear information. Axis 2 shows two groups which can be interpreted as a selection of the swamp-marsh elements with regard to the other groups. Taxa and groups which have been used in the calculations are those representative of humid (climatic or edaphic) conditions. Pollen groups are those used in the synthetic pollen diagram (Fig. 4), despite the following exceptions in order to test the relative contribution of some elements: (1) swamp trees include Taxodiaceae (*Sciadopitys* excluded) and *Nyssa*; (2) the mesothermic elements have been subdivided into two groups according to their local humidity requirements (this includes a riparian association containing *Alnus*, *Salix*, *Populus*, *Liquidambar* and *Parrotia*). Within the herbs, the two most abundant elements, Poaceae and Cyperaceae, have been tested separately. Megathermic and the other mega-mesothermic elements have not been considered because of their low frequencies.

mesothermic elements such as *Engelhardia*, *Carya*, *Pterocarya*, deciduous *Quercus*, *Fagus*, some Cupressaceae, *Juglans*, *Zelkova*, *Carpinus*, *Acer*, etc. Here, the riparian associations were richer in *Alnus p.p.*, *Salix p.p.*, *Liquidambar*, *Parrotia* and *Populus p.p.* Some other Taxodiaceae, such as *Sciadopitys* and those corresponding to the *Sequoia* pollen type, are represented by a small quantity of pollen grains. As considered by Ticleanu and Diaconita (1997), these elements are included in this vegetation group, taking into account their modern habitat which is often altitudinal and in a lower latitudinal range than in Europe, and because they occur relatively frequently in the Lupoaia macroflora (Ticleanu and Diaconita, 1997). Many herbs and shrubs may have been present in such environments, e.g. Asteraceae *p.p.*, Brassicaceae, Polygonaceae, Poaceae *p.p.*, *Buxus*, etc. This vegetation may also have included some Mediterranean elements (*Quercus ilex* type, *Phillyrea*, *Periploca*, *Pistacia*, *Olea*, etc.), as observed in the present-day Colchid vegetation (southern edge of the Caucasus) (Denk et al., 2002). Finally, the vegetation group contained a variety of megathermic elements at non-significant percentages (Euphorbiaceae including *Amanoa*, Mimosaceae including *Entada*, Meliaceae, Sapindaceae, Loranthaceae, Arecaceae, Sapotaceae, Tiliaceae).

(4) At higher altitudes, the composition of the mixed forest would progressively change, with an increasing presence of gymnosperms. First *Cathaya* and *Sciadopitys* would have been present, replaced subsequently by *Cedrus* and *Tsuga*, and finally by *Abies* and *Picea*. Traditionally, North-European palaeobotanists consider that these trees inhabited lowlands (in association with thermophilous elements) during the Early Pliocene, as documented by cones and seeds in the Lower Rhine fluvial plain (Mai, 1995). Today, *Abies* and *Picea* (still living in northern Europe) would be present above 500 m altitude in this area, according to the latitudinal–altitudinal gradient controlling the modern distribution of trees in Europe (Ozenda, 1975, 1989). Therefore, during the Early Pliocene, these conifers may have been repre-

sented by somewhat 'thermophilous' species. However, the presence of *Abies* and *Picea* might indicate cooler conditions in the Middle Pliocene (late Reuverian), when the increase in pollen percentages of these two taxa occurs together with a strong decrease in thermophilous elements (Zagwijn, 1960). At low European latitudes, Early Pliocene floristic conditions were rather different from northern Europe (Zagwijn and Suc, 1984). Indeed, no cones or seeds of *Abies* and *Picea* have been found in lowland or coastal lignites (Rio Maior in Portugal: Diniz, 1984; Arjuzanx in southwestern France: Huard, 1966; Cessenon in southeastern France: Roiron, 1992), and this also applies to the Romanian lignites (Husnicioara, Lupoaia, etc.: Ticleanu and Diaconita, 1997). In southern Europe, only Zanclean pollen diagrams from areas located at the foot of high massifs (Pyrenees, French Massif Central, Alps, Apennines) show high percentages of *Cathaya*, *Cedrus*, *Tsuga*, *Abies* and *Picea* (Suc et al., 1999). Similar records characterise southwestern Romania (Drivaliari et al., 1999; Popescu, present work and unpublished data). In addition, significant increases in *Abies* and *Picea* represent the earliest Northern Hemisphere glacials in pollen diagrams from the Apennines (Bertini and Roiron, 1997; Pontini and Bertini, 2000); this is also supported by the *Picea* macrofossils found in the lignite quarry of Santa Barbara (Bertini and Roiron, 1997). For these reasons, *Abies* and *Picea* are considered to constitute a South-European montane forest belt, even though its temperature range was somewhat higher than its modern analogue in the European massifs. *Cedrus* is considered as growing in an intermediate altitudinal belt. As previously discussed by Suc (1981), at Cessenon (foot of the south French Massif Central) a lignite has been found which is rich (20–40%) in *Cedrus* pollen, but lacks any macrofossils belonging to this genus. Similarly, *Cathaya*, *Keteleeria* and *Tsuga* can be regarded as mid-altitude conifers.

5. Repetitive vegetation changes

The synthetic pollen diagram suggests repetitive changes (Fig. 4A) between (1) a group consisting of the thermophilous taxa (i.e. megathermic elements (such as Mimosaceae, Meliaceae, *Amanoa*, Sapindaceae, Loranthaceae, etc.) and mega-mesothermic elements such as Taxodiaceae (*Sciadopitys* excluded), *Juglans* cf. *cathayensis*, *Engelhardia*, *Myrica*, *Nyssa* cf. *sinensis*, *Distylium*, *Parthenocissus* cf. *henryana*, *Parrotiopsis* cf. *jacquemontiana*, *Microtropis fallax*, Cyrillaceae–Clethraceae, *Leea*, etc. plus Cupressaceae), and (2) a group containing the altitudinal trees (*Tsuga*, *Cedrus*, *Cathaya*, *Abies* and *Picea*). Relative frequencies of these groups are shown in Fig. 4B for comparison with changes in lithology.

On the whole, maxima of thermophilous trees correspond to lignite layers, whereas peaks in altitudinal trees occur within clays. A straightforward explanation of the cause of these alternations might be based on differences in pollen transport. Local vegetation may be well-represented in lignite layers, whereas distant vegetation would be better represented in clay layers as a result of long-distance transport of terrigenous material, including pollen, from altitudinal vegetation belts. In this scenario, lignite deposition would have been unpredictable, caused by changes in the alluvial plain morphology resulting from shifts in the course of the river channel. There are, however, several arguments that contradict such an interpretation:

(1) The continuous lignite layers across the entire basin suggest that there were no local effects of changes in the river channel (Ticleanu and Andreescu, 1988).

(2) Some thermophilous tree maxima occur within clay layers (below lignite VI, below lignite VII, below lignite VIII and above lignite IX); some altitudinal tree maxima occur within lignite layers (base of lignite VI, upper lignite VII, lignite IX).

(3) Today, the pollen frequency of montane trees (*Abies* and *Picea*) is not high in prodeltaic clayey areas, as seen in the northwestern Mediterranean region (Fauquette et al., 1999b).

(4) Mesophilous elements (deciduous *Quercus*, *Carya*, *Pterocarya*, *Liquidambar*, *Carpinus*, *Parrotia*, etc.), which inhabited areas relatively distant from the swamps, show, on the whole, a constant abundance (ranging from 20 to 40% of the pollen

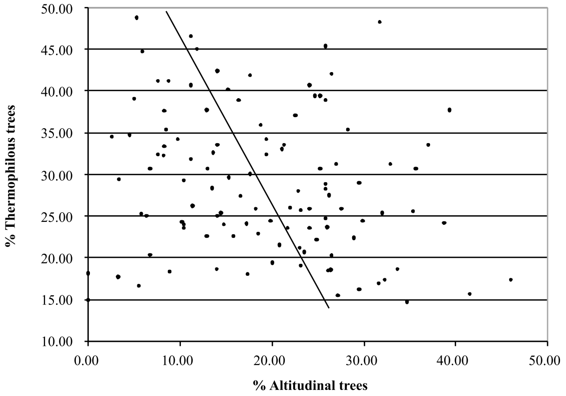


Fig. 6. Linear regression between percentages of thermophilous trees and altitude trees using the reduced major axis method. Regression line is: % thermophilous trees = (−2.228 × altitude trees)+71.476 (slope: −2.228 ± 0.522; intercept: 71.476 ± 145.8). Unbiased correlation coefficients are: Pearson's $r = -0.199$ ($^*P = 0.0375$); Spearman's $r = -0.204$ ($^*P = 0.033$).

sum) independent of the clay–lignite alternations.

(5) Similar variations in pollen spectra between thermophilous elements and altitudinal trees have been recorded in homogenous clay from Early Pliocene sections in the Po Valley (Bertini, 1994).

(6) Close to Lupoaia, the Hinova section (lowermost Pliocene according to nannoplankton evidence; Marunteanu, personal information), entirely constituted by clays, shows very low percentages of altitudinal trees (Popescu, unpublished).

(7) Pollen records between lignites IV and V and above lignite VIII are characterised by relatively low frequencies of altitudinal trees, irrespective of lithology (lignites or clays); on the contrary, frequencies of thermophilous trees are higher in the same intervals. In addition, pollen records between lignites IV and V include some megathermic elements. This suggests that the three main climatic phases of the Early Pliocene could be represented in the Lupoaia section (Brunssumian A or phase P Ia in the Lupoaia borehole F6 up to lignite V; Brunssumian B or phase P Ib between lignites V and VIII in the Lupoaia quarry; Brunssumian C or phase P Ic above lignite VIII in the Lupoaia quarry; Suc and Zagwijn, 1983). The two warm Zanclean phases (P Ia and P Ic) would be characterised by a larger development of swamps in the Dacic Basin while the Zanclean cooling phase (P Ib) would be characterised by reduced swamps and a moderate lowering of altitudinal vegetation belts in the area. This is consistent with the larger extension in space and in thickness of lignites V and VIII (Jipa, personal information).

On the basis of these arguments, a second and more probable interpretation can be made of the long-term thermophilous–altitudinal tree alternations recorded at Lupoaia. These could well indicate successive warm–cool fluctuations corresponding to (1) the development of swamp environments (warmer phases), (2) the descent to lower altitudes of the coniferous forests, with a corresponding increase in their pollen representation in the delta sediments (cooler phases). A correlation analysis has been performed on percentages of thermophilous trees versus those of altitudinal trees for samples 1–110, i.e. in the part of the Lupoaia section where clay–lignite alternations are very contrasted; the linear regression is negative (Fig. 6), and supports this interpretation.

Such regular repetitions need to be juxtaposed with fluctuations in eccentricity in order to test the hypothesis of Van Vugt et al. (2001) who suggested a periodicity of 100 kyr for the lignite layers. Fig. 7 focusses on the period considered by Van Vugt et al. (2001) to correspond to the Lupoaia section deposition. This period is characterised by great contrasts between eccentricity maxima and minima. The global polarity time scale has been chronologically calibrated on the basis of the eccentricity process. In turn, this time scale has been used to establish a chronology for the $\delta^{18}O$ curve, taken from a section in which magnetic reversals have been distinctly identified (Shackleton et al., 1995). The pollen curves may therefore be related to the calibrated time scale using the palaeomagnetic reversals of the Lupoaia section. This gives two independent lines of evidence to allow testing of the hypothesis of eccentricity forcing of lignite formation.

In general, the $\delta^{18}O$ curve indicates a relative cooling phase corresponding to the C3n.2n Chron. However, the pollen record indicates a

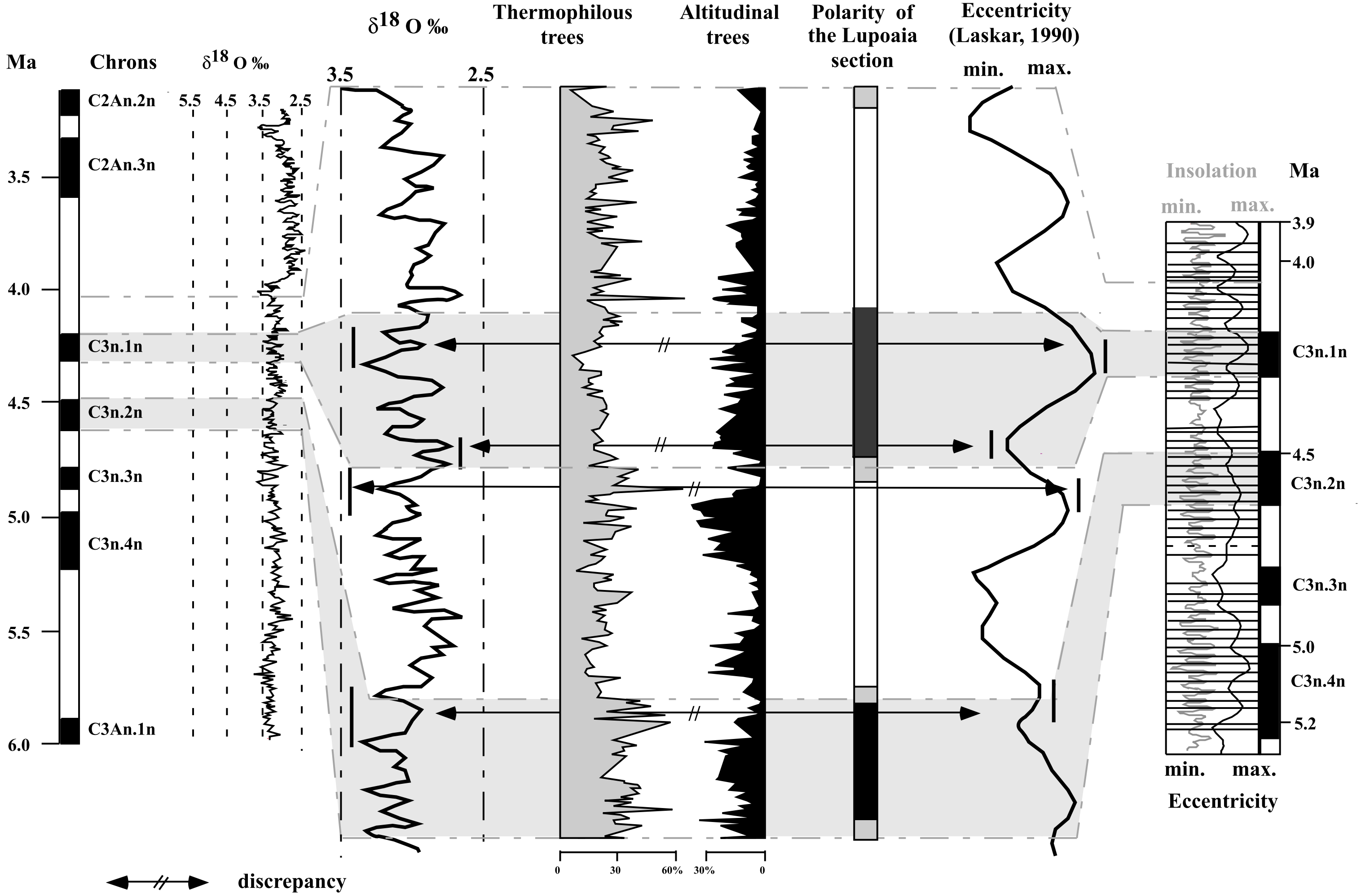


Fig. 7. Curves of thermophilous elements versus altitudinal trees (see Fig. 4B) are compared to eccentricity curve (Laskar, 1990) and to a reference $\delta^{18}O$ curve (Shackleton et al., 1995) within the chronological frame proposed by Radan and Radan (1998) and Van Vugt et al. (2001). Some discrepancies between pollen curves and $\delta^{18}O$ and/or eccentricity curves are indicated close to magnetic reversals for comparisons within similar accurate chronological intervals.

warm climate (high percentages of thermophilous trees) during this normal polarity event. The interval between Chrons C3n.2n and C3n.1n corresponds to a warmer period according to the δ^{18}O record; this is also supported by changes in eccentricity. However, this is in harmony with pollen data from the reverse interval in the lower part of the Lupoaia section, which are indicative of cooler conditions (decrease in thermophilous elements). The same line of reasoning cannot be applied to the upper Lupoaia section, since the differences between the pollen record and δ^{18}O curve are not so well marked for the time interval between the early C3n.1n Chron and the early C2An.3n Chron. A more detailed examination of the magnetic reversals shows some major discrepancies (points 1, 3, 4 below) between the pollen record and eccentricity and/or δ^{18}O curves, and one (point 2) of minor importance:

(1) The reversal at the end of the C3n.2n Chron occurs just before the end of a prolonged maximum in eccentricity and should therefore correspond to a general cooling period (see also the δ^{18}O reference curve). This is in contradiction to the high abundance of thermophilous trees in the Lupoaia pollen record, which exists for some time prior to this period.

(2) The reversal at the onset of the C3n.1n Chron corresponds to a transition from a maximum eccentricity to a moderate minimum eccentricity, i.e. from a cooler to a warmer period. This is clearly seen in the δ^{18}O reference curve, but appears to be in contradiction with high thermophilous tree percentages in the Lupoaia pollen record. However, the imprecise definition of the position of this magnetic reversal reduces the strength of this argument.

(3) Following this event, there is a reduction in eccentricity and the δ^{18}O curve indicates a warmer climate, in contradiction with the relatively large percentages of altitudinal trees in the Lupoaia pollen record.

(4) The upper reversal of C3n.1n Chron corresponds to the transition from a maximum eccentricity to a relative minimum eccentricity, i.e. from cooler to relatively warmer climatic conditions (see also the δ^{18}O reference curve). During the same period, however, the Lupoaia pollen records shows an evolution from warmer (high percentages in thermophilous trees) to cooler (increase in altitudinal trees) conditions.

Due to these incompatibilities, an attempt has been made to correlate the Lupoaia section with a somewhat earlier period than proposed by Van Vugt et al. (2001). In this concept, tested using a similar comparative approach, the two normal polarity episodes have been assigned to C3n.3n and C3n.2n Chrons, respectively, as indicated on Fig. 8. The period is dominated by a long maximum in eccentricity, interrupted by some brief relative minima. This chronology gives an almost complete correspondence between the Lupoaia pollen curves and the global climatic reference curves (eccentricity and δ^{18}O). This is particularly obvious at the magnetic reversals:

(1) The reversal at the end of the C3n.3n Chron corresponds to a minimum eccentricity, indicating a warm period that is supported by both δ^{18}O values and by large percentages of thermophilous trees in the Lupoaia pollen record.

(2) The reversal at the onset of the C3n.2n Chron corresponds to a short minimum eccentricity within a long maximum phase, i.e. to warmer conditions within a long cooling period. This is in good agreement with the δ^{18}O curve and the maximum of thermophilous trees between two maxima of altitudinal trees in the Lupoaia pollen record.

(3) The reversal at the end of the C3n.2n Chron matches the transition from minimum to maximum eccentricity at the end of the long period of maximum eccentricity. This is consistent with the warmer phase expressed both by the δ^{18}O reference curve and thermophilous trees in the Lupoaia pollen record.

Similar inferences may be made for all the major and minor concordances shown in Fig. 8.

It is therefore proposed that the previously estimated correlation of the Lupoaia section (Radan and Radan, 1998; Van Vugt et al., 2001) has to be changed to correspond with the normal Chrons C3n.3n and C3n.2n. In this case, the evolution of the regional climate as reflected by the pollen record is fully consistent with global climatic evolution (insolation and δ^{18}O record). Such a chronological assignment is supported by

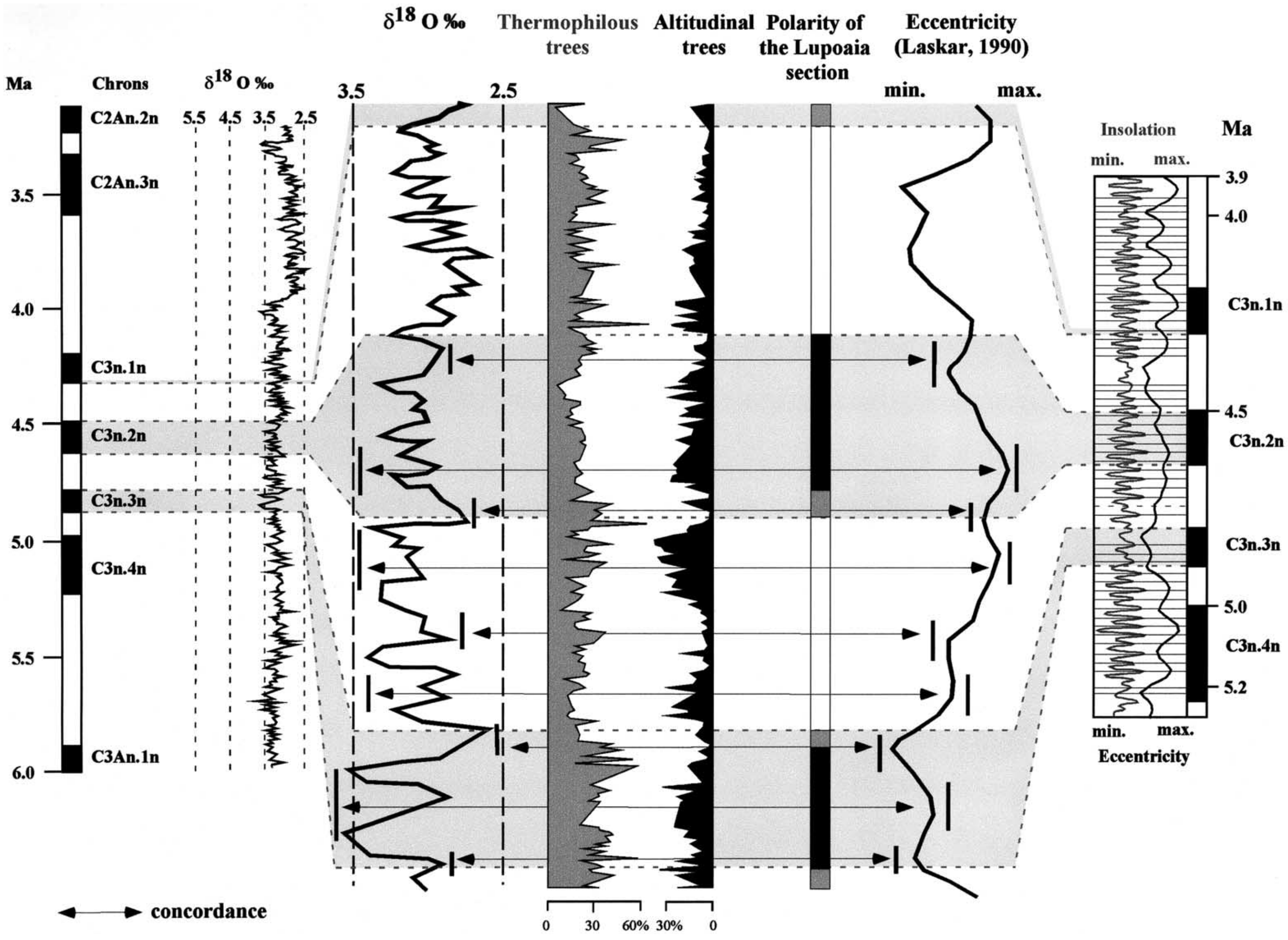


Fig. 8. Curves of thermophilous elements versus altitudinal trees (see Fig. 4B) are compared with the eccentricity curve (Laskar, 1990) and a reference δ^{18}O curve (Shackleton et al., 1995) using a chronological frame, which is one chron older than that proposed by Radan and Radan (1998) and Van Vugt et al. (2001). Some concordances between pollen curves and δ^{18}O and eccentricity curves are indicated close to magnetic reversals for comparisons within similar accurate chronological intervals.

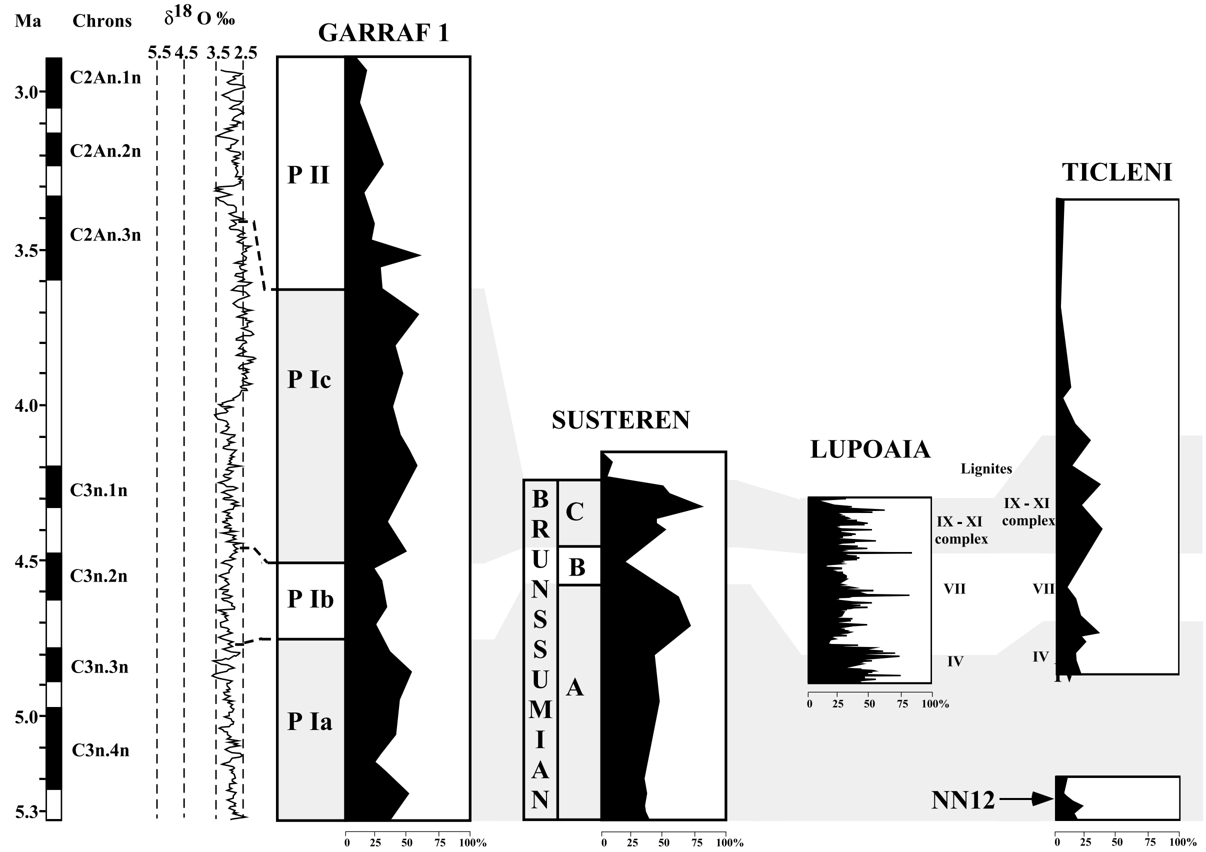
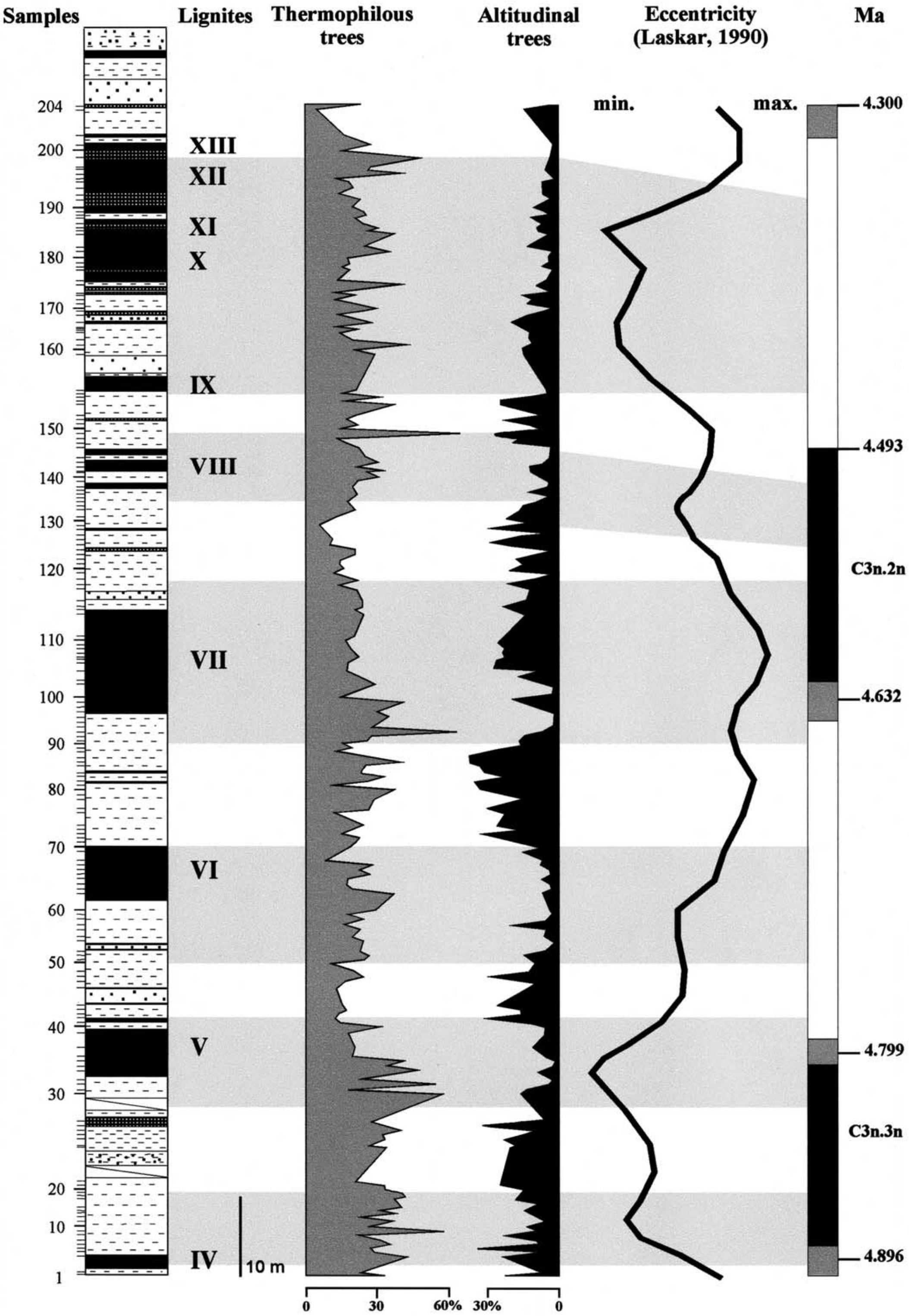


Fig. 9. Place of the Lupoaia pollen diagram in the frame of the regional (Ticleni: Drivaliari et al., 1999) and European climatostratigraphies (Susteren in The Netherlands: Zagwijn, 1960; Garraf 1 in the northwestern Mediterranean region: Suc and Cravatte, 1982) and the reference global $\delta^{18}O$ curve (Shackleton et al., 1995). Climatostratigraphic relationships are based on the respective curves of thermophilous trees focussing on the warm Early Pliocene phase (Brunssumian in The Netherlands, pollen phase P I in the Mediterranean). The Lupoaia pollen diagram covers the upper Brunssumian A (pollen zone P Ia in the Mediterranean) to the lower Brunssumian C (pollen zone P Ic in the Mediterranean). Position of lignites IV, VII and IX–XI complex is indicated in support of climatostratigraphic relationships between the Ticleni and the Lupoaia sections.

the mammal fauna, especially by the presence of a primitive *Mimomys* in lignite VIII. In addition, the proposed age of the Lupoaia section would be fully consistent with the climatic subdivision of the Early Pliocene in Europe (Zagwijn, 1960; Suc, 1982; Suc and Zagwijn, 1983), in which a cooling period (Brunssumian B = phase P Ib) is observed between two warm periods (Fig. 9). The Lupoaia section belongs almost completely to this cooling period, which has also been observed in the Ticleni borehole. This is further supported by the regional lignite stratigraphy, cooling being centred around lignite VII (Drivaliari et al., 1999) (Fig. 9).

The Van Vugt et al. (2001) hypothesis is confirmed: lignite layers seem to occur every 100 kyr.

Fig. 10. Cyclic responses in the Lupoaia pollen record of thermophilous and altitudinal trees to eccentricity. Chronology of palaeomagnetic reversals after Lourens et al. (1996). Shaded areas represent warm parts of the climatic cycles inferred from comparison of thermophilous tree maxima with eccentricity minima. Lithology: see Fig. 2.


Samples
Lignites
Thermophilous trees
Altitudinal trees
Eccentricity (Laskar, 1990)
Ma
204
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
1
XIII
XII
XI
X
IX
VIII
VII
VI
V
IV
10 m
min.
max.
4.300
4.493
C3n.2n
4.632
4.799
C3n.3n
4.896
0
30
60%
30%
0

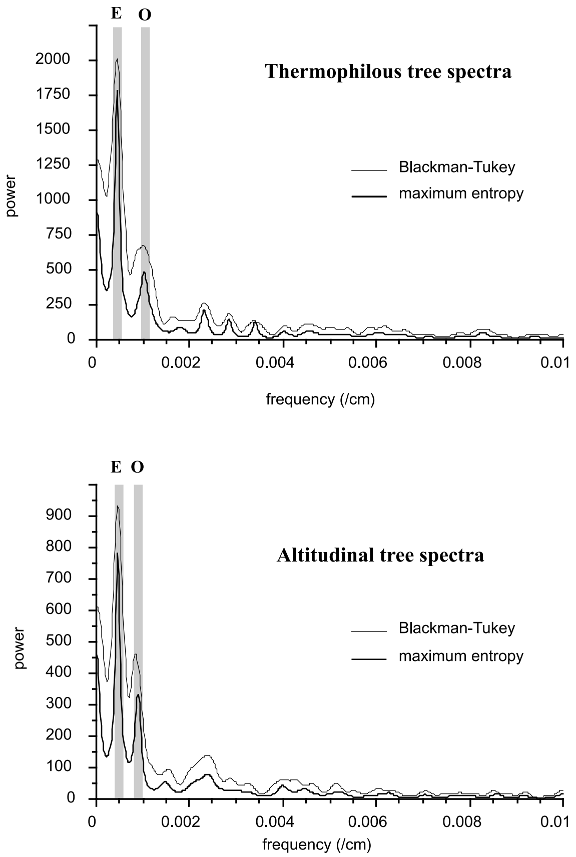


Fig. 11. Spectral analysis of thermophilous elements and altitude trees. E, peak considered as representative of eccentricity period; O, peak considered as representative of obliquity period. The most significant peak E corresponds to 0.0005 as frequency. The correlative period is inverse to frequency (expressed in cm), i.e. 2000 cm.

They are linked to minimum eccentricity. A simple estimate, based on the time separating the two most distant magnetic reversals obviously recorded in the Lupoaia section (4.799 (end of C3n.3n Chron)–4.493 Ma (end of C3n.2n Chron) according to Lourens et al., 1996), indicates a period of 306 kyr. This period includes three maxima of altitudinal trees and three relative maxima of eccentricity (100-kyr period) (Fig. 10). A spectral analysis of thermophilous elements and altitudinal trees has been performed with respect to thickness of the section (Analyseries Program: Paillard et al., 1996). Both groups show a strong spectral peak which has been calculated as located at a thickness of 20 m (Fig. 11). This corresponds to a time period of approximately 87 kyr, and can be considered consistent with the period of eccentricity, when the changes in sedimentation rate that probably differentiated lignites from clays are taken into account.

Pollen concentration can provide information on preservation and/or changes in sedimentation rate (Suc, 1984b); low values may be associated with higher sedimentation rate (pollen grains diluted within a lot of terrigenous particles), and high values with a low sedimentation rate. Fig. 12 shows variations in pollen concentration along the Lupoaia section. The highest values (> 10 000 pollen grains/g of sediment) mostly correspond to lignite layers, with the exception of some samples from borehole F6. Examination of the respective thickness of clays and lignites within each eccentricity cycle (sands are excluded because they probably represent a short time-interval), shows that lignites represent less than half a cycle, where one cycle equals the clay layer and the overlying lignite (Fig. 10): lignite V = 25% of the cycle; lignite VI = 40% of the cycle; lignite VII = 25% of the cycle; lignite VIII = 35% of the cycle. For three of these lignites (V, VI, VII), the related minimum eccentricity is considerably shorter in time than the maximum part of the eccentricity curve corresponding to the underlying clays. However, lignite VIII seems thinner as may be expected on the basis of the eccentricity curve, which shows a minimum of longer duration. In contrast, the thickness of lignites IX plus X–XIII (> 60% of the cycle) seems to be in agreement with the relatively long duration of the corresponding minimum in the eccentricity curve. The pollen concentration appears to vary independently of the variation in thickness within the cycles (high pollen concentration for lignites VI, VII and X–XIII; low pollen concentration for lignites V and VIII). As a consequence, pollen concentration seems to be more linked to preservation and possibly to xylite abundance in some lignites. This may explain the scarcity, and occasional absence of pollen grains in some samples.

The eccentricity-forced pollen cycles (thermophilous plants versus altitudinal trees) and lithology cycles (clay–lignite alternations) suggest that the inferred ages throughout the studied section

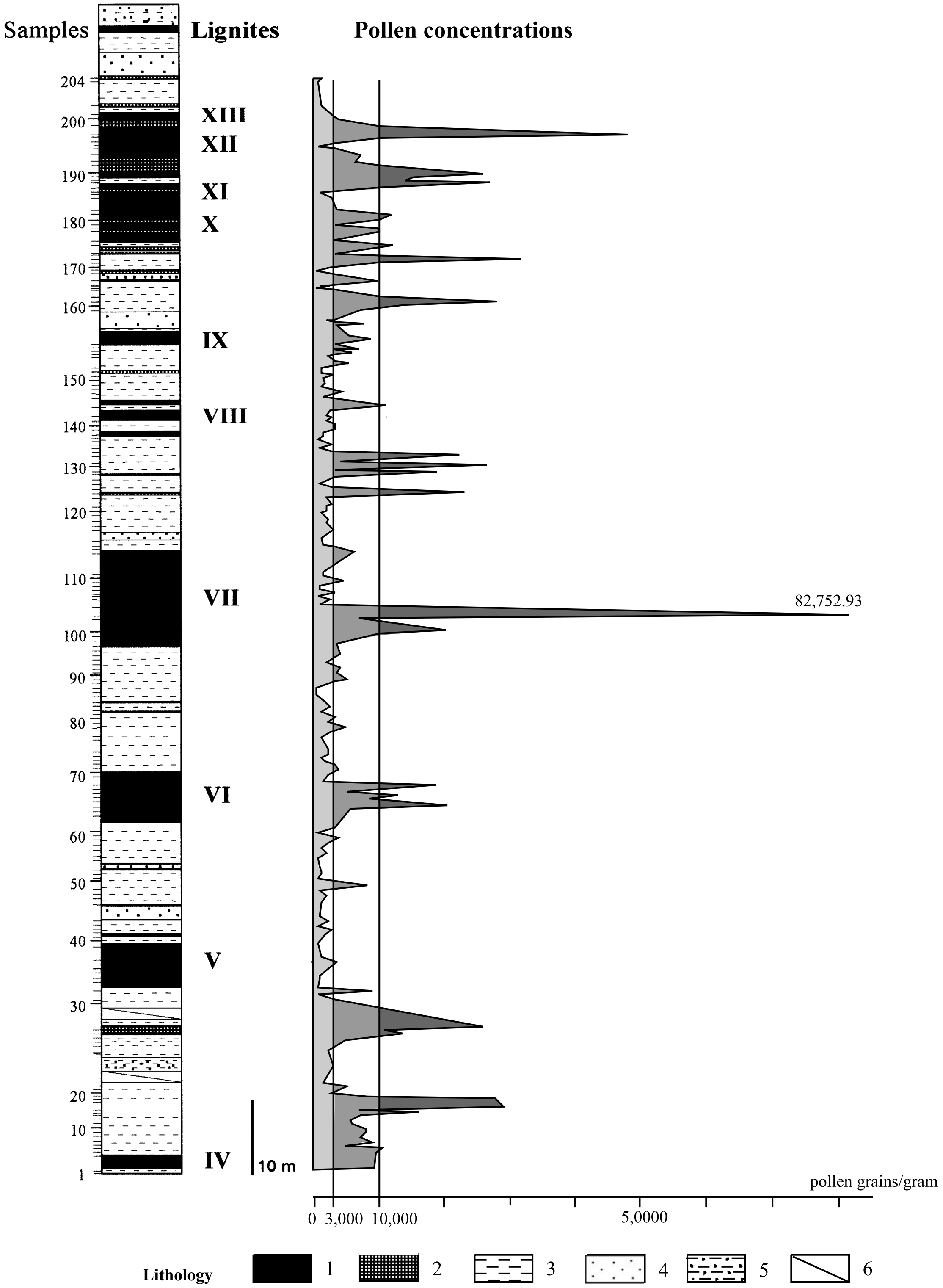


Fig. 12. Pollen concentration along the Lupoaia section. Lithology: see Fig. 2.

correspond well with respect to the eccentricity chronology. As a consequence, it is proposed that (1) the undetermined polarity zone in the basal part of the section should belong to the reversed polarity interval prior to C3n.3n Chron (the reversal should occur within the clays located above lignite IV), (2) the reversal at the end of Chron C3n.3n should occur within the undetermined polarity zone, more precisely at the top of lignite V, and (3) the undetermined polarity zone located at the top of the Lupoaia section should immediately precede the following normal interval, i.e. the C3n.1n Chron (Fig. 10). The latter inference is based on both the eccentricity chronology and the close relationships between the $\delta^{18}O$ reference curve and the thermophilous tree curve in the Lupoaia pollen record (Fig. 9). Taking this information into account, the studied Lupoaia section would represent a time span of about 600 kyr, i.e. from about 4.90 to about 4.30 Ma. The three climatic phases of the Early Pliocene in the Lupoaia pollen record (see above: warm phase ending with lignite V, cooler phase between lignites V and VIII, warmer phase starting with lignite VIII; Fig. 10) may be the expression of the 400-kyr cycles of eccentricity overprinting the 100-kyr cycles (see Figs. 8 and 10).

6. Conclusions

High-resolution pollen analyses of the Lupoaia section (borehole F6 and quarry) have (1) allowed the reconstruction of the Early Pliocene vegetation of southwestern Romania, and (2) provided evidence of repetitive changes in vegetation. The results show two opposed vegetation belts: thermophilous trees, which were located in low altitudes of the Dacic Basin, and altitudinal trees which probably grew in the Carpathians. During cooling periods, this second group migrated to lower altitudes, and their pollen grains partly masked the local production in the alluvial plain. In this region, lignite deposition corresponds to warm phases under continuously humid conditions.

These vegetation changes and the clay–lignite alternations are forced by eccentricity. A detailed comparison between pollen data and global climatic fluctuations (provided by eccentricity and $\delta^{18}O$ curves) has led to a change in the chronological assignment of the section, previously based on a preliminary interpretation of palaeomagnetic measurements (Radan and Radan, 1998; Van Vugt et al., 2001). The revised chronological assignment is in accordance with the mammal fauna, whereas the regional climatic fluctuations are consistent with the global climatic evolution. The Lupoaia section covers a period between approximately 4.90 and 4.30 Ma and represents a time span of about 600 kyr. The section completely includes the C3n.3n and C3n.2n Chrons. In addition, it is proposed that the section ends at the onset of the C3n.1n Chron.

Climatically, the Lupoaia section covers:

(1) The end of the Early Pliocene warm phase (Brunssumian A in northern Europe and P Ia phase in the northwestern Mediterranean region; Suc and Zagwijn, 1983).

(2) The entire Early Pliocene cooling (Brunssumian B in Northern Europe and P Ib phase in the Northwestern Mediterranean region; Suc and Zagwijn, 1983).

(3) The beginning of the late Early Pliocene warm phase (Brunssumian C in Northern Europe and P Ic phase in the Northwestern Mediterranean region; Suc and Zagwijn, 1983).

The main Early Pliocene climatic subdivisions are now documented for the east of Europe but appear more complex. Other areas (for example at the base of mountains) may provide similarly detailed records when studied with high-resolution pollen investigation.

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