Palaeogeography, Palaeoclimatology, Palaeoecology xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Integrated stratigraphy of the Early Miocene lacustrine deposits of Pag Island (SW Croatia): Palaeovegetation and environmental changes in the Dinaride Lake System

Gonzalo Jiménez-Moreno [a,*], Arjan de Leeuw [b], Oleg Mandic [c], Mathias Harzhauser [c], Davor Pavelić [d], Wout Krijgsman [b], Alan Vranjković [d]

[a] Departamento de Estratigrafía y Palaeontología, Universidad de Granada, Fuente Nueva S/N, 18002, Granada, Spain
[b] Palaeomagnetic Laboratory Fort Hoofddijk, Faculty of Geosciences, Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands
[c] Geological-Palaeontological Department, Natural History Museum Vienna, Burgring 7, A-1010 Wien, Austria
[d] Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Pierottijeva 6, HR-10000 Zagreb, Croatia

ARTICLE INFO

Article history:
Received 23 December 2008
Received in revised form 18 May 2009
Accepted 30 May 2009
Available online xxxx

Keywords:
Pollen
Vegetation
Climate change
Magnetostratigraphy
Cyclostratigraphy
Orbital forcing
Long-lived lakes
Dinaride Lake System
Early Miocene
Croatia

ABSTRACT

An integrated stratigraphic study of a Neogene lacustrine succession on the Pag Island (Croatia), combining quantitative pollen analysis, magnetostratigraphy, cyclostratigraphy, biostratigraphy and gamma-ray measurements, provides new insights into orbitally controlled variations in palaeo-vegetation and depositional patterns in the Dinaride Lake System. The quantitative palynological record shows a cyclical pattern of vegetation changes that closely corresponds to sedimentological patterns. The intervals with a high abundance of thermophilous and xeric indicators, suggesting a warm and dry climate, generally coincide with intervals of frequent lignite deposition and shallow lake facies. This suggests that both records are dominantly controlled by variations in past climatic conditions and lake level. Our data show two large-scale warming and shallowing-upward cycles, which are interpreted to be forced by the ~100 kyr eccentricity cycle of the Earth's orbit. Magnetostratigraphic data of the examined section reveal a long (113 m) reversed polarity interval, followed by a 7 m thick interval of normal polarity at the top. The inferred depositional rate of ~0.3 mm/yr, combined with biostratigraphic constraints by mollusks, suggests that the most logical correlation of the reversed interval is to chron C5Cr. This indicates that the Pag succession was deposited between 17.1 and 16.7 Ma and that it corresponds to the Burdigalian Stage of the Early Miocene, and the regional Karpatian Stage of the Central Paratethys. The high relative percentage of thermophilous pollen taxa, *Engelhardia* and *Taxodium*-type being the most prominent, generally indicates a subtropical humid climate for the SW Croatian part of the Dinaride Lake System. The observed warming trend is possibly related to the onset of the Miocene Climatic Optimum.

1. Introduction

The Dinarids, and other areas of southern Europe, are very interesting from a floristic point of view because of the Miocene, Pliocene and Pleistocene relics in their present-day floras (Quézel and Médail, 2003; Thompson, 2005). These areas served as a refuge for thermophilous plants that otherwise would have vanished from Eurasia during the Pleistocene glaciations (Quézel and Médail, 2003). In addition, these plants must also have survived various long term climatic changes that have taken place since the beginning of the Miocene (~24 Myr ago). The influence of the astronomical climate forcing on vegetational changes has been recognized in the pollen records of the Mediterranean and Paratethys regions (e.g. Combourieu-Nebout and Vergnaud-Grazzini, 1991; Bertini, 2001; Popescu, 2001; Jiménez-Moreno et al., 2005; Popescu et al., 2006; Kloosterboer-van Hoeve et al., 2006; Jiménez-Moreno et al., 2008a,b), but such detailed records are lacking from the Dinarids.

The Miocene sediments of the Dinaride Lake System (DLS), a tectonically induced series of coal bearing basins in Croatia and Bosnia–Herzegovina (Fig. 1), are rich in plant fossils and thus provide a good opportunity to study palae-ovegetation patterns. Several studies have previously described and interpreted the palaeobotanical record of the DLS (Radimsky, 1877; Engelhard, 1883, 1900, 1901, 1902a, b, 1903, 1904a,b, 1910, 1912, 1913; Katzer, 1918, 1921; Vasković, 1931; Polić, 1935; Veen, 1954; Pantić, 1957; Weyland et al., 1958; Muftić and Behlilović, 1961; Pantić, 1961; Muftić and Luburić, 1963; Pantić and Bešlagić, 1964; Muftić, 1964; Behlilović and Muftić, 1966; Pantić et al., 1966; Muftić, 1970; Jurišić-Polšak et al., 1993; Krizmanić, 1995; Pavelić et al., 2001; Jurišić-Polšak and Bulić, 2007), but generally a pollen classification devoid of the relationship with the botanical nomenclature was applied, which makes climatic interpretations difficult.

* Corresponding author. Tel.: +34 958 243347; fax: +34 958 248528.
E-mail address: gonzaloj@ugr.es (G. Jiménez-Moreno).

0031-0182/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.palaeo.2009.05.018

Fig. 1. Geographic position of the studied section representing the ancient Lake Pag deposits. This lake developed during Lower Miocene at the southwestern margin of the Dinaride Lake System (DLS). The illustration shows the maximum extent of the DLS (after Krstić et al., 2003) prior to Middle Miocene disintegration and marine flooding of its northeastern environments by the Central Paratethys Sea.

The scarceness of quantitative palaeobotanical records from the Dinarids, and the absence of an accurate chronostratigraphic control have thus far prevented a good understanding of the Miocene and Pliocene vegetation and climate history of the western Balkan Peninsula.

In this study, we apply an integrated stratigraphic approach combining magnetostratigraphy, cyclostratigraphy and biostratigraphy to obtain reliable time control for the Miocene deposits of Lake Pag, which was positioned at the SW margin of the DLS. Detailed palynological and sedimentological analyses will be performed to interpret the vegetation and climatic history of the northern proto-Mediterranean margin. Special emphasis will be given to detect cyclic variations in the proxy records, and to investigate if these correspond with the Milankovitch frequency bands of the astronomical climatic forcing. This study is part of a larger project that aims at a better understanding of the flora, vegetation and climate dynamics of the DLS during the Miocene (e.g. Jiménez-Moreno et al., 2008b).

2. Geological setting

The Miocene sedimentary rocks on the Island of Pag (SW Croatia) represent the northwestern margin of the DLS: a palaeobiogeographic entity which, at times of its largest extent, stretched across the Dinarides and into the southern Hungarian plain (Krstić et al., 2003). Since the Oligocene, the region played an important role as a land barrier between the Central Paratethys and the western Tethys/proto-Mediterranean Sea. The Dinaride Lakes are not only characterized by a rich fossil plant record, but also by a spectacular autochthonous mollusk evolution and radiation as reflected by unique events of diversification in some of the stratigraphically younger basins (Kochansky-Devidé and Slišković, 1972, 1978; Harzhauser and Mandic, 2008a,b; Mandic et al., 2009).

Our study area represents the NE margin of the imbricated Adriatic carbonate platform, and is located alongside the frontal thrust of the Dinaride Western Thrust Belt (Tari, 2002). The main phase of tectonic shortening started in the Eocene and resulted in NW–SE oriented folding. Eventually, the platform disintegrated because of underthrusting of the Dinarides by the Adriatic Block. Middle Eocene flysch sediments, deposited in the Dinaride foredeep and formed on top of this block, represent the last marine influence in the region (Ćorić et al., 2008). Continued underthrusting subsequently resulted in continentalisation during the Late Eocene. Miocene activation of NW–SE dextral strike–slip faults generated a multitude of depressions that formed the DLS. It was triggered by the initiation of northward movement of the Adriatic block, while eastward underthrusting below the Dinaridic Block continued.

The Miocene lacustrine deposits on Pag are restricted to two elongated, NW–SE striking basins, which presently comprise 1.51 km^2 and 0.16 km^2 surface areas, respectively (Fig. 2). These basins developed in two isolated syncline cores subsiding up to 500 m deep, at subvertical and sub-parallel marginal faults. Their fossil and lithological records suggest that lacustrine deposition occurred synchronously. The emerged anticline in between reflects the original relief at the time of deposition. The SW basin occupies a 9.5 km long tectonic depression, but most of the Miocene deposits are hidden below the Pleistocene and Holocene debris. The lacustrine sediments transgressively onlap the Cretaceous basement and attain a maximal thickness of 143.60 m (Mamužić and Sokač, 1967). The basal unit comprises low quality lignite commercially exploited in the 19th century (see Fig. 2 for mine position). Late Jurassic to Early Cretaceous evaporites are present at depths of about 2000 m from the basin's decollement (Mamužić and Sokač, 1967).

Our studied succession (Crnika section) in the Pag Island is located in the NE basin, about 10 km SE from the tourist resort Novalja. We sampled along a 1 km NW–SE oriented exposure on the southwestern shore of the Pag Gulf (NW tip and section top is at GPS/WGS84 point 44.510208, 14.965375, Figs. 2–4). The largest part of the basin infill currently lies below the tide line and is only exposed along the coast. It consists of lacustrine marls, clays and sands that dip about 15° in NNW direction (320/15), sub-parallel to the coastline. The succession discordantly overlies the Eocene flysch and/or Eocene to Cretaceous

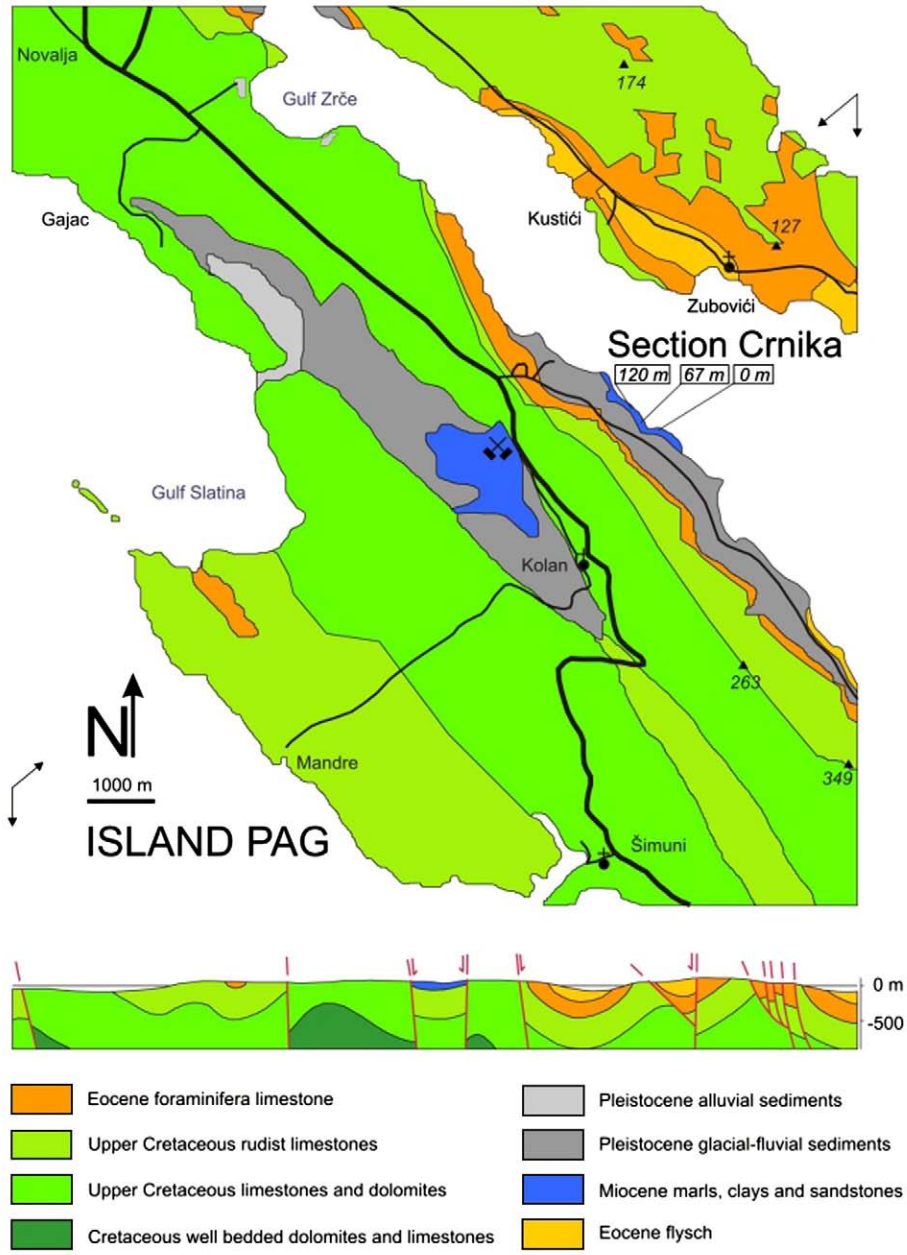


Fig. 2. Geological map and cross-section showing the geologic and tectonic setting of the Lake Pag deposits (blue) (modified after Mamužić et al., 1970). The Miocene lacustrine deposits are distributed in two parallel sub-basins with a distance of about 1 km. Both basins are of tectonic origin, developed on a single subsided block on top of a syncline structure. The cross-section shows a flower structure at its NE margin suggesting strike–slip faulting as the mechanism triggering basin formation. Note the position of the studied section in the northeastern sub-basin and the abandoned small scale mine in the southwestern sub-basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

carbonate platform deposits. The top is formed by an angular discordance, superimposed by subhorizontal Pleistocene debris deposits (Fig. 4). Landward continuation of the lacustrine deposits is impeded by the overlying Pleistocene debris.

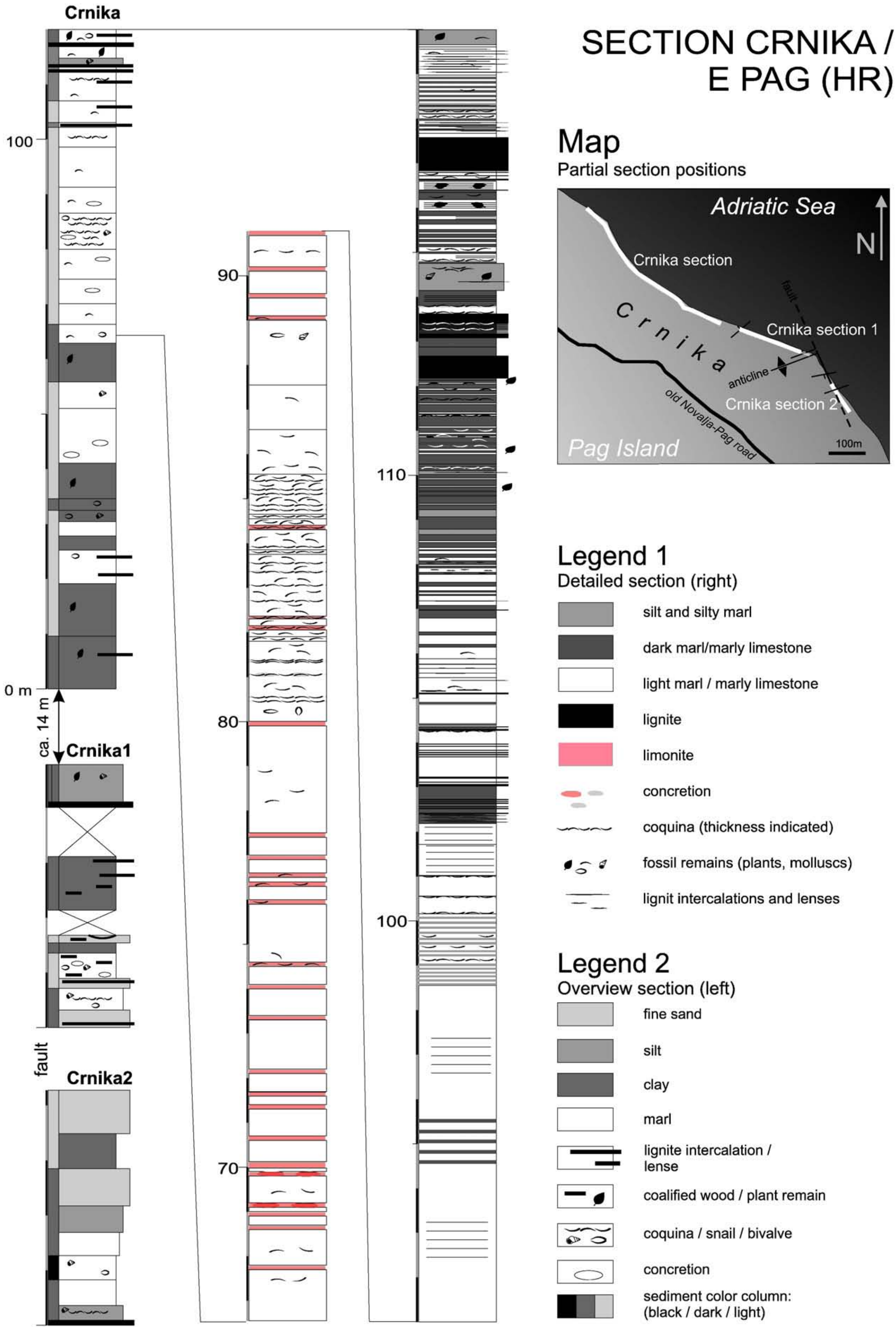
3. Methods

3.1. Sedimentology and gamma-logging

The Crnika section represents the longest and best outcrop on the Pag Island and is divided in three partial sections named (from NW to SE) Crnika, Crnika1 and Crnika 2 (Fig. 3). The top part of the main Crnika section is beautifully exposed, but the lower part is partially covered by beach debris. These debris were artificially removed at carefully chosen sampling positions to achieve the longest continuous interval possible for magnetostratigraphic sampling. Crnika 1 is characterised by several thick unexposed intervals, and the upper part of Crnika 2 is complicated through faulting and folding (Fig. 3). The detailed sedimentological description, gamma-ray logging and palynological sampling have consequently been restricted to the top part of the main Crnika section (Fig. 3). Gamma-ray logging was carried out with a hand-held gamma-spectrometer measuring counts per second at vertical distances of 10 cm. Gamma-ray intensity is in function of clay mineral input and secondary uranium enrichment by organic matter such as lignite, respectively.

3.2. Palaeomagnetism

Fifty-two standard palaeomagnetic cores were sampled with an average stratigraphic resolution of 2–3 m (Figs. 5 and 6), using a hand-


Crnika
100
0 m
ca. 14 m
Crnika1
fault
Crnika2
90
80
70
110
100
SECTION CRNIKA / E PAG (HR)
Map
Partial section positions
Adriatic Sea
N
Crnika section
Crnika
fault
Crnika section 1
anticline
Crnika section 2
old Novalja-Pag road
Pag Island
100m
Legend 1
Detailed section (right)
silt and silty marl
dark marl/marly limestone
light marl / marly limestone
lignite
limonite
concretion
coquina (thickness indicated)
fossil remains (plants, molluscs)
lignit intercalations and lenses
Legend 2
Overview section (left)
fine sand
silt
clay
marl
lignite intercalation / lense
coalified wood / plant remain
coquina / snail / bivalve
concretion
sediment color column: (black / dark / light)

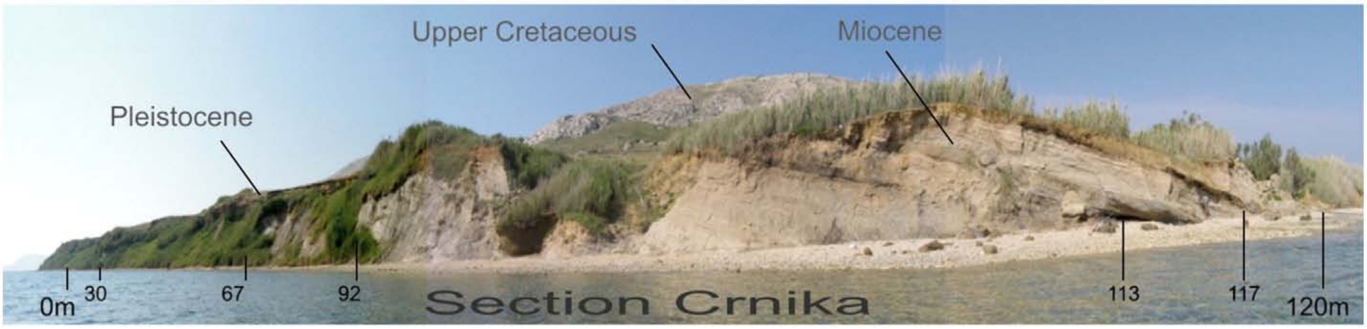


Fig. 4. Panorama of the studied outcrop section and position of key beds. The Miocene lake deposits exposed along the southwestern coast of the Gulf of Pag dip northwards by about 15°. A Pleistocene terrace cuts the Miocene outcrop at about 5 to 10 m topographic height. The hill above consists of Cretaceous and Eocene limestones.

held electric drill with water-cooled diamond-coated drill bits. The orientation of all samples was measured with a magnetic compass. Measured directions were corrected for the local magnetic declination, adding 2.5° east. The obtained cores were sliced in two parts and stepwise demagnetized. One specimen of each sample level was thermally demagnetized, while the other half was subjected to robotized alternating field (AF) demagnetization. The natural remanent magnetization (NRM) of all samples was measured after each step on a 2G Enterprises DC Squid cryogenic magnetometer (noise level $3 \cdot 10^{-12}$ Am^2). Heating took place in a magnetically shielded, laboratory-built furnace applying temperature increments of 15–20 °C. AF demagnetisation was carried out applying 5–20 mT increments up to 100 mT using a degausser interfaced with the magnetometer by a laboratory-built automated measuring device. The characteristic remanent magnetisation (ChRM) was identified through examination of decay-curves and vector end-point diagrams (Zijderveld, 1967). ChRM directions were calculated by principal component analysis (Kirschvink, 1980).

Furthermore, several rock-magnetic experiments were performed to identify the carriers of the magnetization. An alternating gradient magnetometer (Princeton Measurements Corporation, MicroMag Model 2900 with 2T magnet, noise level $2 \times 10-9$ Am2) was used to successively measure hysteresis loops and FORC diagrams at room temperature. Sample masses ranged from 20 to 43 mg. Hysteresis loops were measured for 3 representative samples (Figs. 5 and 6) in order to determine the saturation magnetization (Ms), the saturation remanent magnetization (Mrs) and coercive force (Bc). These parameters were determined after correction for the paramagnetic contribution on a mass-specific basis. To further assess the magnetic domain state, the effects of magnetic interactions, and the magnetic mineralogy, FORC diagrams were measured for the same 3 representative samples. Signal-to-noise ratios were sufficient to enable use of a maximum smoothing factor (SF) of 5 (Pike et al., 2001).

3.3. Palynology

Sixty samples rich in palynomorphs were studied for pollen analysis from the top part of the Crnika section (Figs. 7 and 8). Samples were processed according to the following procedure: 10–20 g of sediment was treated with cold HCl (35%) and HF (70%), removing carbonates and silicates respectively. 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 were not considered. A minimum of 150 pollen grains (*Pinus* and indeterminable Pinaceae excluded) was counted in each sample (Cour, 1974). Pollen identification was accomplished to the lowest taxonomic level possible by comparing the fossils with their present-day relatives using published keys and comparing with pollen atlases. The percentages of pollen taxa were calculated, and the results were plotted in simplified pollen diagrams (Figs. 7 and 8). The results were plotted using TILIA and zoned using CONISS (Grimm, 1993) using the following pollen types: *Pinus* and indeterminate Pinaceae, *Engelhardia* and *Taxodium*-type (Fig. 7). To highlight basic patterns, thermophilous taxa (including Arecaceae, Rutaceae, Euphorbiaceae, *Alchornea*-type, Caesalpiniaceae, *Distylium*, Menispermaceae, Cyrillaceae–Clethraceae, *Engelhardia*, *Platycarya*, Taxodiaceae, Sapotaceae, *Symplocos*, Rubiaceae, *Mussaenda*-type and *Microtropis fallax*), Mediterranean plants (*Olea* and *Quercus ilex-coccifera* type) and *Pinus* and other conifers (including *Pinus* and indeterminable Pinaceae, *Cathaya* and *Cedrus*) were grouped together and plotted in Fig. 8. We also calculated the ratio of thermophilous to *Pinus* and other conifers (T/P ratio) (Fig. 8). Jiménez-Moreno et al. (2008b) showed that the relationship between thermophilous plants and *Pinus* and other conifers can be very useful in identifying important vegetation, eustatic and climate changes. Pollen zonation of the detailed pollen diagram has been done taking into account the cluster analysis obtained by CONISS (Grimm, 1993) and the variations in relative percentages of the main taxa occurring in the studied section (see explanation below; Fig. 7).

4. Results

4.1. Sedimentology and palaeontology

The Crnika 2 section is ~40 m thick and represents a single upward coarsening parasequence. A basal lignite bed is superposed by light gray fossiliferous clayey silts. A 24 m thick upward coarsening succession follows, grading from dark brown and black clayey marls, via mollusk bearing silty marls and marly silts, into dark brown clayey fine sands. Finally, light gray sandy clays with some lignite intercalations grading into clayey fine sand are present in the top part. The rich mollusk assemblage of Crnika 2 comprises hydrobiid snails, *Theodoxus*, *Brotia*, *Melanopsis*, *Pisidium* and *Mytilopsis*, all characteristic fresh-water lake inhabitants. The upward extension towards Crnika 1 section is highly uncertain because of severe tectonic disturbances (Fig. 3).

The scattered outcrops of Crnika 1 are comprised of ~8 m dark sands at the lowermost part, grading upward into dark brown and gray marls with lignite intercalations and mollusk shell beds (Fig. 3). Light gray fine sands grading into clayey marls with mollusks and tree trunks are followed by dark clays and sands with channel structures.

Fig. 3. Sedimentological log of the Crnika section. Note the additional sections Crnika 1 and Crnika 2 positioned along the SE coast line continuation to the main section. The partial section Crnika1 is bounded at the top by about 14 m stratigraphic interval covered by beach debris. It comprises several small outcrops, likely bounded by covered areas in between. Its base has been logged in the anticline core up to the lower tide line. The Crnika 2 section with similar bedding orientation to other two sections ends on top with a fault.

Please cite this article as: Jiménez-Moreno, G., et al., Integrated stratigraphy of the Early Miocene lacustrine deposits of Pag Island (SW Croatia): Palaeovegetation and environmental changes..., Palaeogeography, Palaeoclimatology, Palaeoecology (2009), doi:10.1016/j.palaeo.2009.05.018

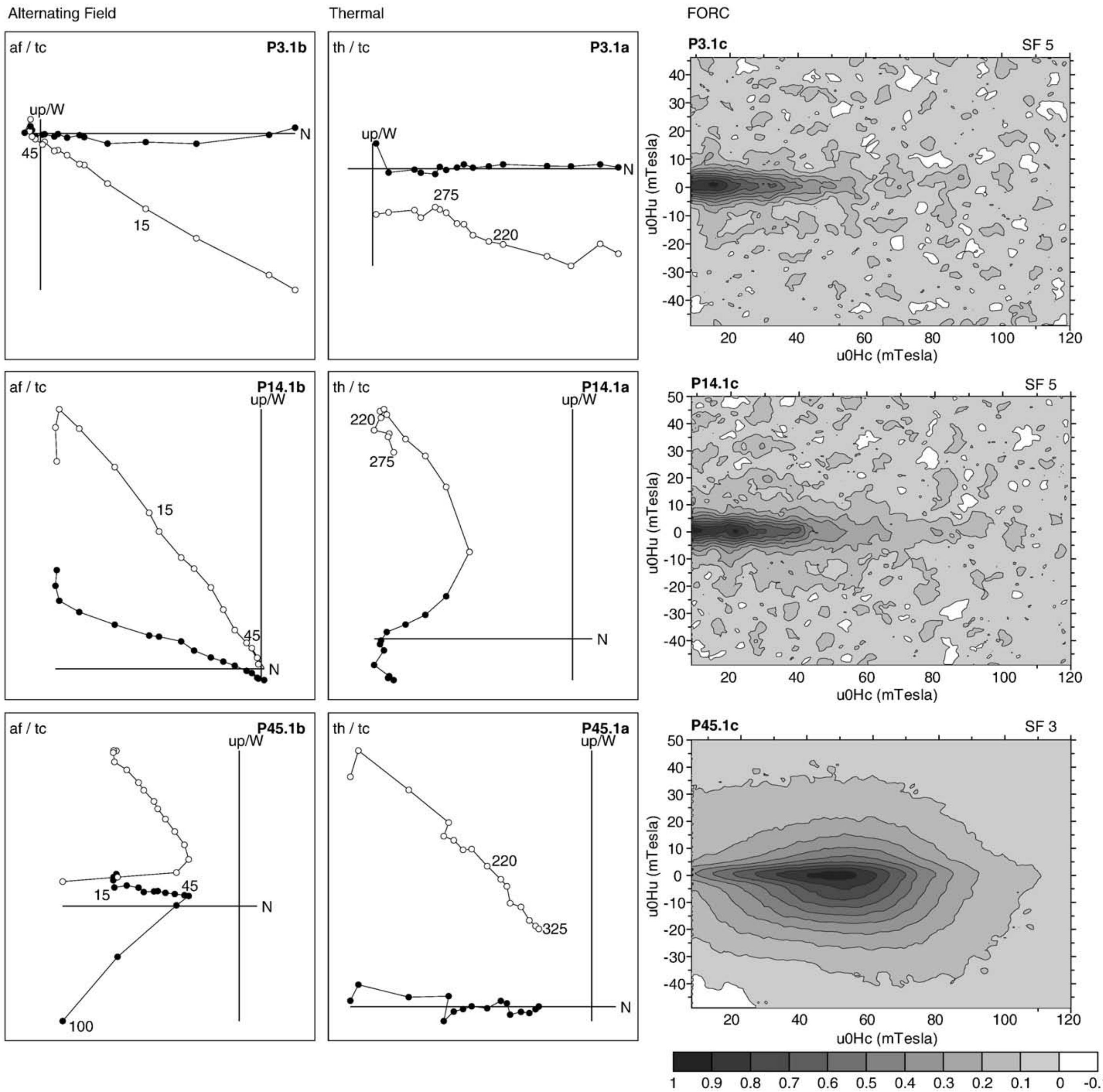


Fig. 5. Palaeomagnetic and rock-magnetic measurements for samples P3, P14 and P45. a) Zijderveld alternating field demagnetization diagrams. Relevant field strengths are indicated. b) Zijderveld thermal demagnetization diagrams. Relevant temperatures are indicated. c) First-order reversal curve diagrams. SF indicates the smoothing factor.

An interval of ~10 m of organic rich clays, with lignite components and lenses, is observed in the upper part. Finally, a ~7 m thick interval of dark brownish clayey silt with plant remains and snails superposes a single lignite bed. The mollusk assemblage contains conspicuous specimens of the large *Brotia escheri* (Brongniart 1822). The tentative upward continuation to the main Crnika section is separated by a non-exposed interval of ~14 m.

Marls and clays dominate the 120 m thick Crnika succession (Fig. 3 right, Fig. 4). The lower 20 m includes scattered lignite intercalations. The topmost 20 m comprises, besides lignite intercalations, three coal seams, each about 0.5 m thick and demonstrating a coarsening upward trend by increasing silt component. The peaks in the gamma-ray record (Fig. 8) demonstrate that the lignites contain accumulated radioactive matter. The macrofossil content is restricted to mollusks and carbonated plant remains. The latter are mainly bounded to 4 intervals of enhanced organic matter content: around the base and at 35 m, 60 m, and the section top. Mollusks are scattered in the lower half of the section with *Mytilopsis* and *Pisidium* restricted to interval between 25 and 35 m. Mollusks prevail the macrofossil record from 55 m upward. *Pisidium* dominates intervals of monotonous pelitic sedimentation, whereas *Mytilopsis* is the main constituent of the coquinas characterizing the topmost 50 m of the succession. These mollusk assemblages are distinctly different from the coquinas in Sections Crnika 1 and 2.

The upper part of the Crnika Section (Figs. 3 and 8) comprises two shallowing-upward parasequences. The lower parasequence starts with monotonous marls that contain thin reddish limonite layers bearing scattered *Pisidium* shells. It ends with a ~5 m thick interval

Please cite this article as: Jiménez-Moreno, G., et al., Integrated stratigraphy of the Early Miocene lacustrine deposits of Pag Island (SW Croatia): Palaeovegetation and environmental changes..., Palaeogeography, Palaeoclimatology, Palaeoecology (2009), doi:10.1016/j.palaeo.2009.05.018

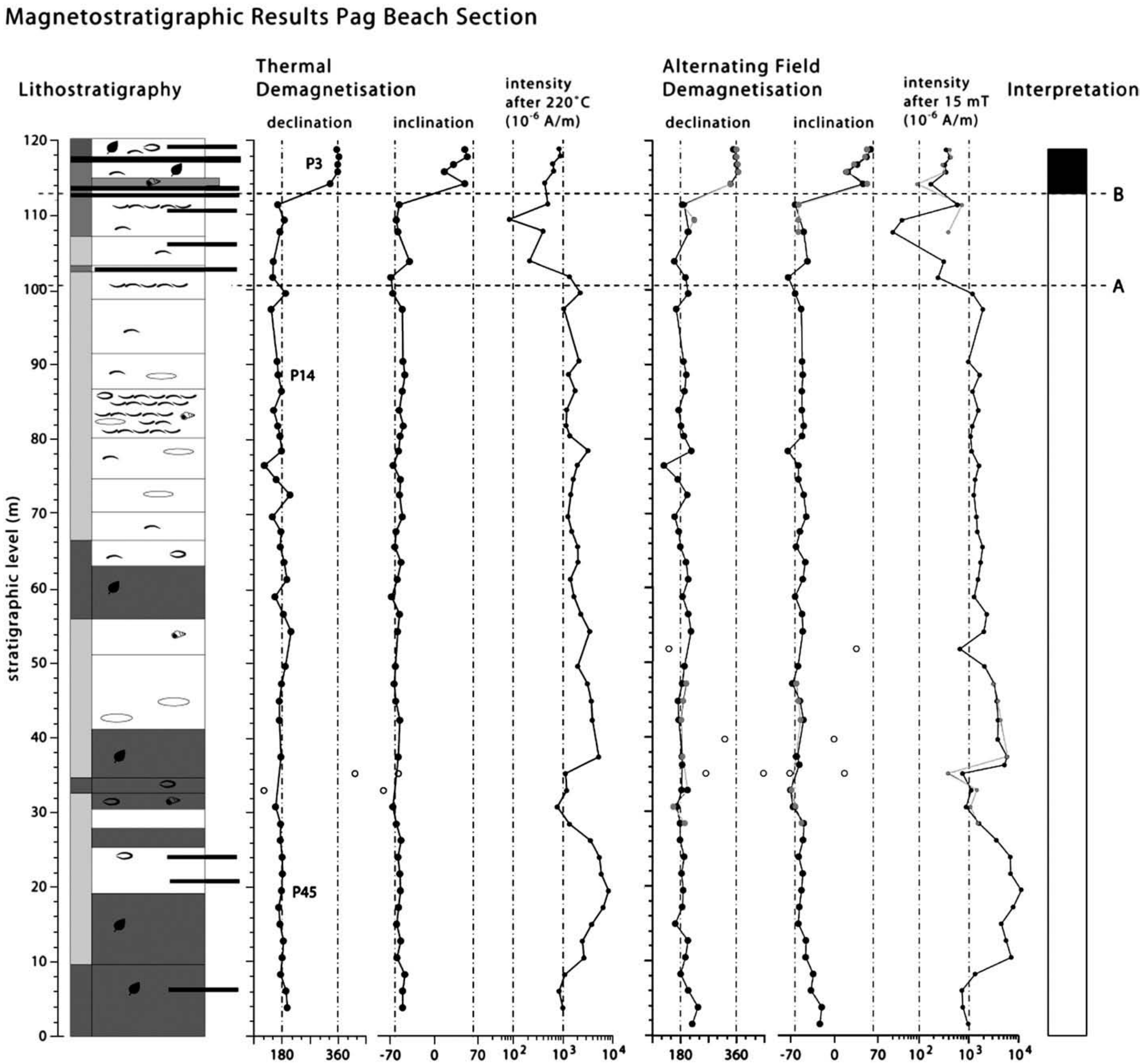


Fig. 6. Lithological log, declination, inclination and intensity results of good quality (closed) and poor quality (open) ChRM from thermal and alternating field demagnetization respectively. Utmost right column shows the corresponding magnetostratigraphy for the investigated section on the Pag Island.

(from 80.5 to 85.5 m) marked by dense *Mytilopsis* shell accumulations. The second parasequence starts again with marls rich in *Pisidium* shells and reddish interlayers and grades upward into parallel bedded marl. The first silt intercalations start at ~20 m below the top of the section, together with lignite intercalations and *Mytilopsis* coquinas. The interval ends with lignite seams at intervals between 102–104 m and 106–108 m, in which coquinas with large disarticulated *Mytilopsis kucici* (Brusina, 1907) prevail. The gamma-ray measurements carried out for that topmost 50 m of the section reproduce the described sedimentological pattern with peaks positioned in the parasequence tops (Fig. 8).

4.2. Palaeomagnetism

Thermal demagnetization of the samples shows that the total NRM is composed of two components (Fig. 5). A low temperature component is mostly removed at 220 °C. Alterations often occur above 275 °C as indicated by a sheer rise in NRM intensity and randomization of the NRM directions. Since these alterations prohibit determination of the ChRM at higher temperatures, the ChRM directions were generally established between 220 and 275 °C. Alternating field demagnetization of the samples corroborates the results of the thermal demagnetization. It reveals once more that the total NRM is composed of two components (Fig. 5). A low field component is mostly removed at 15 mT. In the interval between 0 and 60 m, samples suffer from gyroremanence at fields above 45 mT. This indicates the presence of an iron sulfide, most likely greigite. The acquired gyroremanent magnetization distorts demagnetizations diagrams for these samples above 45 mT. Since this effect might, although perhaps only slightly, contribute to the NRM of the majority of the other samples above 45 mT as well, all ChRM directions were established between 15 and 45 mT.

Please cite this article as: Jiménez-Moreno, G., et al., Integrated stratigraphy of the Early Miocene lacustrine deposits of Pag Island (SW Croatia): Palaeovegetation and environmental changes..., Palaeogeography, Palaeoclimatology, Palaeoecology (2009), doi:10.1016/j.palaeo.2009.05.018

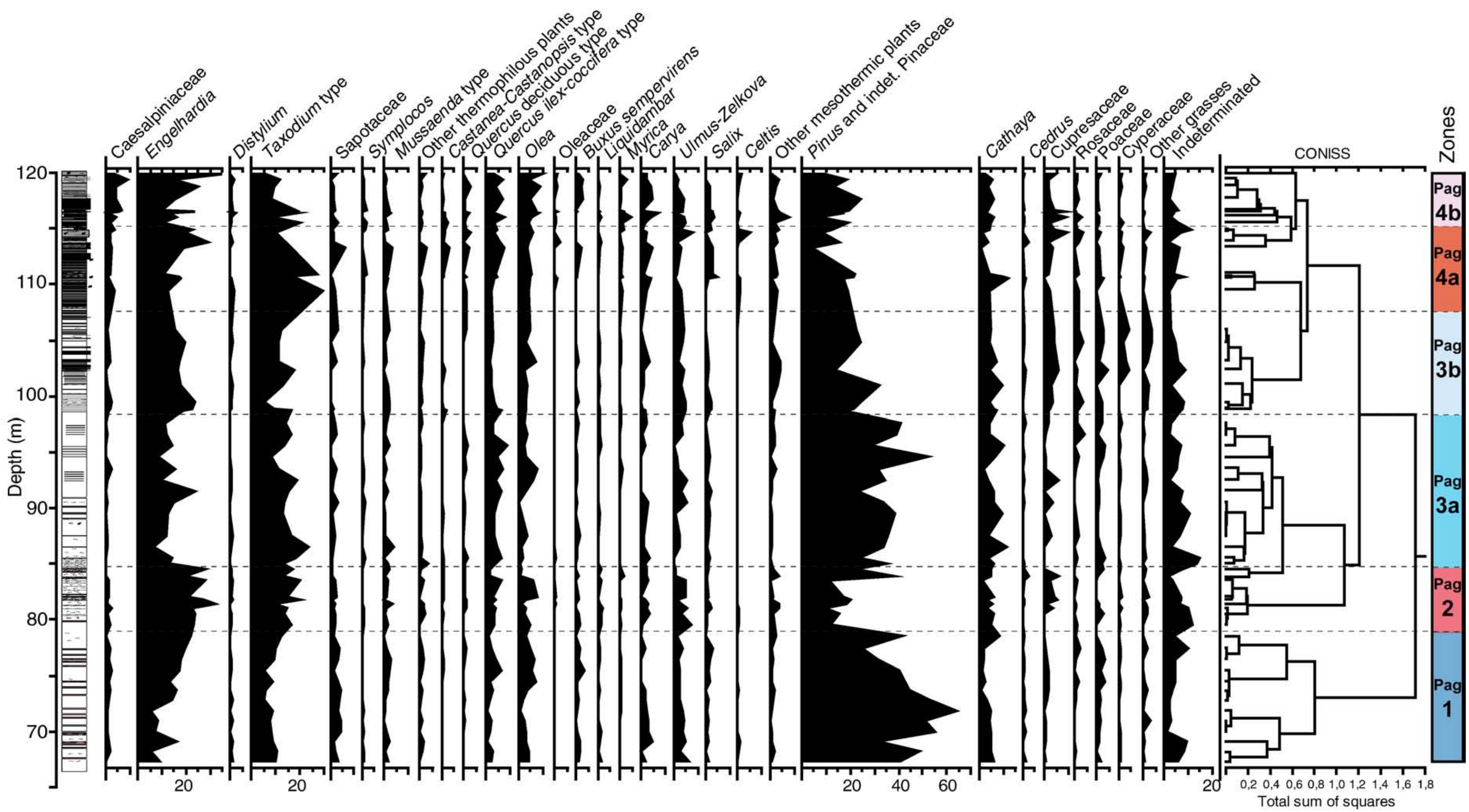


Fig. 7. Simplified detailed pollen diagram of the Pag section showing percentages of taxa. The group "other thermophilous plants" includes Arecaceae, Chloranthaceae, Rutaceae, Rubiaceae, Menispermaceae, Cyrillaceae–Clethraceae, Euphorbiaceae, *Alchornea*-type and *Platycarya*. Other mesothermic plants includes *Pterocarya*, *Betula*, *Alnus*, *Eucommia*, *Fagus*, *Vitis*, *Fraxinus* and *Cornus*. Other grasses comprises Brassicaceae, *Plantago*, *Artemisia*, Ranunculaceae, *Ephedra*, Urticaceae, Amaranthaceae–Chenopodiace, Asteraceae, *Galium*-type, Liliaceae and Apiaceae. Pollen zonation has been made taking into account the cluster analysis using CONISS (Grimm, 1993) and the variations in relative percentage of the main taxa occurring in the studied section. On the left, the lithological log of the studied Crnika section (see legend in Fig. 8).

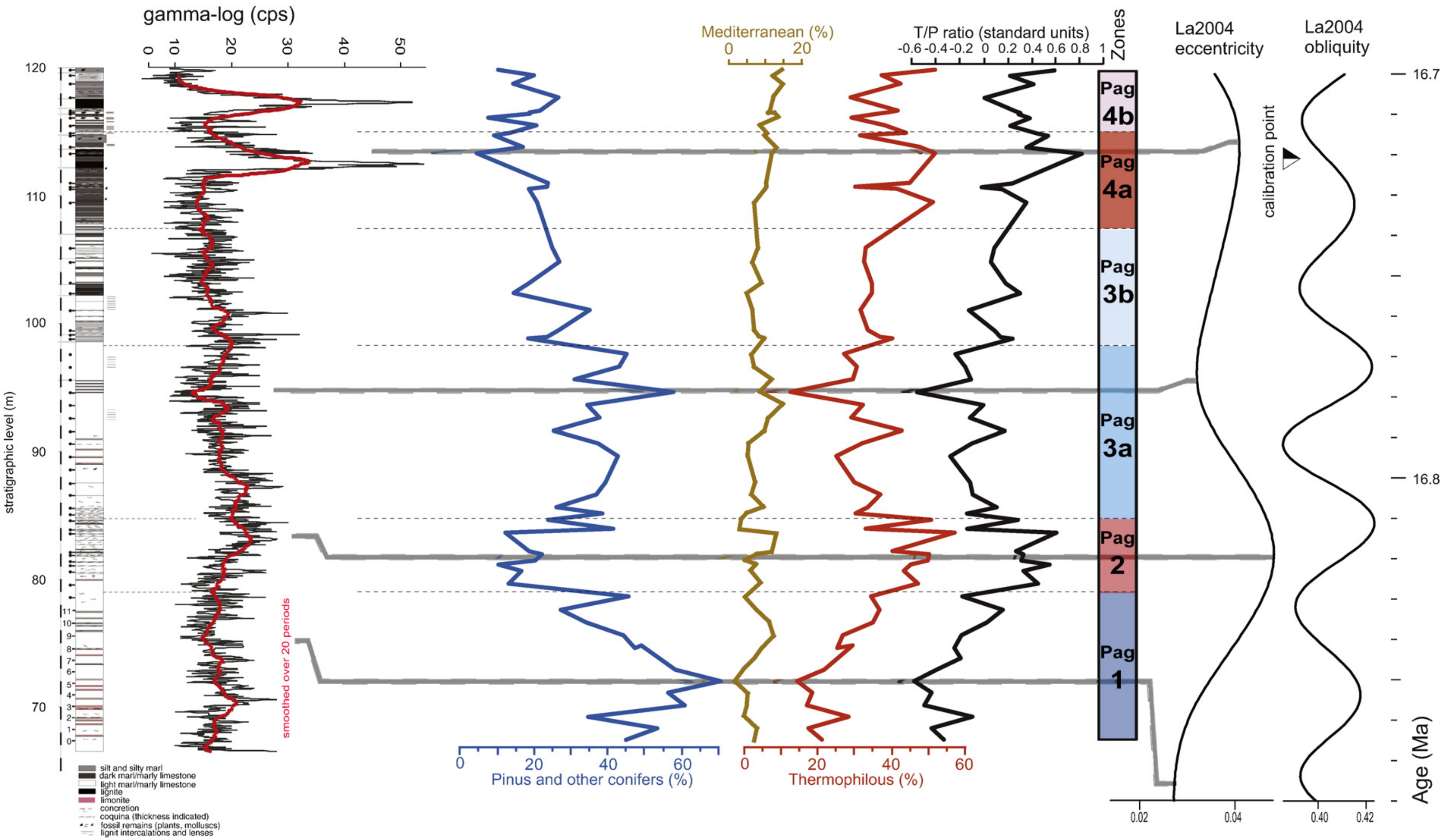


Fig. 8. Comparison of the lithological, gamma-log and pollen records from the Pag section (Early Miocene, SW Croatia) and their correlation to eccentricity and obliquity curves of Laskar et al. (2004). From left to right, lithologic log, gamma-lag, percentage of *Pinus* and other conifers, percentage of Mediterranean plants (including *Olea* and *Quercus ilex-coccifera* type), percentage of thermophilous plants, *T*/*P* ratio [Thermophilous-*Pinus* and other conifers ratio; $(P-T)/(P+T)$] and pollen zonation identified in this study (see text for more explanation). Note the general coincidence between high-frequency deposition of coquinas and lignites with high percentages of thermophilous and *T*/*P* ratios. The position of the pollen samples is indicated by dots.

Please cite this article as: Jiménez-Moreno, G., et al., Integrated stratigraphy of the Early Miocene lacustrine deposits of Pag Island (SW Croatia): Palaeovegetation and environmental changes..., Palaeogeography, Palaeoclimatology, Palaeoecology (2009), doi:10.1016/j.palaeo.2009.05.018

The NRM intensities after heating up 220 °C typically range between 0.8 and 10 mAm^{-1}. Only in the top 20 m of the section are intensities between 0.08 and 0.9 mAm^{-1} and thus significantly lower. This drop in intensity coincides with a change in lithology from pure marl to coal bearing marl. The NRM intensities after application of a 15 mT field also typically range between 0.7 and 10 mAm^{-1}. Again, for the top 20 m of the section, intensities are significantly lower, and range between 0.02 and 0.7 mAm^{-1}. The section was divided into three intervals on the basis of Zijderveld diagrams and intensity plots. Interval 1 (0–60 m) is characterized by high intensity NRM and gyroremanence above 45 mT. Interval 2 (60–101 m) is characterized by high intensity NRM without gyroremanence. Interval 3 (101–120 m) is characterized by lower intensities. From each of these intervals one sample was selected for rock-magnetic measurements.

The FORC diagram of sample P45 (Fig. 5) has contours that close around a single domain (SD) peak at $B_c = 50$ mT. The central peak has considerable spread and is centered slightly below $B_u = 0$, which indicates relatively strong magnetic interaction. The diagram is similar to those previously published for greigite (Roberts et al., 2000). Moreover, samples from this interval are characterized by gyroremanence if demagnetized with alternating fields stronger than 45 mT, which is also indicative for greigite. Greigite is commonly present in most lacustrine environments and recently shown to be able to carry a stable and reliable palaeomagnetic signal (Vasiliev et al., 2007, 2008). The FORC diagrams of P14 and P3 (Fig. 5) are characteristic for multi-domain (MD), non-interacting magnetic minerals (Roberts et al., 2000; Pike et al., 2001). Contour lines are centered at 20 mT. When subjected to alternating field demagnetization, the NRM intensity of the samples from these intervals decays to zero near field strengths of 100 mT. Therefore we conclude that in both intervals the main carrier of the magnetization is a detrital, multi-domain magnetite. This mineral is also known to be a stable, reliable carrier of the ChRM.

Demagnetisation diagrams are overall of good quality (Fig. 5) and in most cases the ChRM directions can be reliably determined (Fig. 6). Only 5% of the data were rejected. The major part of the section shows reversed polarity, while the very top part is of normal polarity. The polarity reversal occurs between 111 and 114 m. and does not coincide with the lithology related drop in intensity at 101 m.

4.3. Pollen stratigraphy

We determined four pollen zones in the topmost 53 m of the section (see pollen diagram; Fig. 7). Subzones were differentiated within zones Pag-3 and Pag-4, highlighting transitional phases.

Pag-1 (from ca. 67–79 m in the Pag section) pollen spectra were mainly characterized by the highest abundances of *Pinus* and indeterminable Pinaceae, reaching percentages higher than 60% at ca. 71.9 m in the section. *Taxodium*-type and *Engelhardia* reached minimum percentages during this pollen zone, with values around 5% (Fig. 7). The T/P ratios were also the lowest during this zone; peaking (−0.6) at 71.9 m. Mediterranean plants were very poorly represented, with minimum mean values of about 5% (Fig. 8).

Pinus and indeterminable Pinaceae decreased considerably, until about 12%, during Pag-2 zone (79–84 m). Thermophilous pollen types, including *Engelhardia* and *Taxodium*-type, increased to percentages about 33 and 22% respectively. T/P ratios also increased to average values above 0.4.

Pag-3 (from ca. 84−107.5 m) zone is subdivided into two subzones — Pag-3a (84–98 m) and Pag-3b (98–107.5 m). In the older subzone *Pinus* and indeterminable Pinaceae showed an important increase with peaking values above 57% at around 94.5 m. On the other hand, thermophilous plants (mostly *Engelhardia*) and T/P ratios strongly decreased showing minimum values at the same depth. Pag-3b was characterized by decreasing values of *Pinus* and indeterminable Pinaceae and increasing thermophilous plants and T/P ratios (Fig. 8).

Pag-4 (from ca. 107.5 m-top of the section) pollen spectra were characterized by a significant increase in thermophilous plants (mainly *Taxodium*-type and *Engelhardia*), Mediterranean plants (*Olea* and *Quercus ilex-coccifera* type) and T/P ratios. Pag-4b is differentiated from Pag-4a because of a slight increase in *Pinus* and indeterminable Pinaceae and a decrease in T/P ratios. Mediterranean plants are maxima during this pollen zone, with values slightly below 20%.

5. Discussion

5.1. Age of the Crnika section

A first-order age constraint for the studied succession is given by regional biostratigraphic data, based on the evolutionary series of endemic mollusks (Kochansky-Devidé and Slišković, 1972, 1978, 1980). Two basic evolutionary mollusk stages have been regarded for the DLS successions (Kochansky-Devidé and Slišković, 1972, 1978, 1980). The lower stage is defined by the co-occurrence of primitive dreissenid bivalves such as *Mytilopsis kucici* and clivunellids, which is an endemic gastropod family unknown outside DLS (Kochansky-Devidé & Slišković, 1972). The First Occurrence Datum (FOD) of Clivunellid assemblages in the thick sedimentary sequences of the Livno and Sarajevo basins of the DLS in Bosnia–Herzegovina is found superimposed on Proboscidean-bearing deposits (Kochansky-Devidé and Slišković, 1978, 1980). The Proboscidean FOD is an important biostratigraphic event in Europe, with approximate maximal age of c. 17.5 Ma, suggested from $^{40}Ar/^{39}Ar$ age of 16.99 ± 0.16 Ma obtained from the rhyolite tuff near Nemti in N Hungary (Palfy et al., 2007) and consequently attributed to the Burdigalian (Fig. 9).

The upper stage starts after the clivunellid extinction and is characterized by progressive evolutionary, highly specialized, species of dreissenid bivalves such as the DLS endemic, giant, lucinid shaped *Mytilopsis aletici* (Kochansky-Devidé and Slišković, 1978). The FOD of *Mytilopsis aletici* in the Sinj basin of the DLS in S Croatia is calibrated to the upper part of chron C5Br (Mandic et al., 2007, 2009), estimated at ~15.2 Ma and corresponding to the Langhian (Fig. 9). The presence of *Mytilopsis kucici* alongside the clivunellid genera *Clivunella* and *Delminiella* in the Crnika sections, previously documented by Jurišić-Polšak and Bulić (2007), thus indicates a late Burdigalian to early Langhian age for the Pag lacustrine deposits.

The magnetic polarity pattern of the Pag section (Fig. 6) consists of a long reversed period with a transition to a normal period at the top. Based on the late Burdigalian–early Langhian age constraint, the most likely correlations to the Geomagnetic Polarity Time Scale are to chron C5Br, C5Cr or C5Dr, respectively (Fig. 9). Since the presence of a progressive *Mytilopsis aletici*-type evolutionary assemblage would be expected in C5Br and because C5Dr is positioned below the clivunellid FOD, the most logical correlation is to chron C5Cr (Fig. 9). Our preferred correlation thus infers an age for the Crnika sections from approximately 17.2 to 16.7 Ma, implying a minimum sedimentation rate of 0.22 m/kyr.

5.2. Flora and vegetation

European Miocene floras are very similar to the one growing today in subtropical to temperate SE China (Suc, 1984; Axelrod et al., 1996; Jiménez-Moreno, 2005; Jiménez-Moreno et al., 2005; Jiménez-Moreno, 2006; Jiménez-Moreno et al., 2007a,b, 2008a,b) and the vegetation inferred in this study could also be compared to the one growing in that area today (Wang, 1961). The following plant ecosystems can be distinguished in the pollen data from the Crnika section:

1) a swamp (mainly Taxodium-type, Myrica and Nyssa) and riparian environment with Salix, Alnus, Carya, Carpinus cf. orientalis, Celtis, Ulmus-Zelkova and Liquidambar;

Please cite this article as: Jiménez-Moreno, G., et al., Integrated stratigraphy of the Early Miocene lacustrine deposits of Pag Island (SW Croatia): Palaeovegetation and environmental changes..., Palaeogeography, Palaeoclimatology, Palaeoecology (2009), doi:10.1016/j.palaeo.2009.05.018

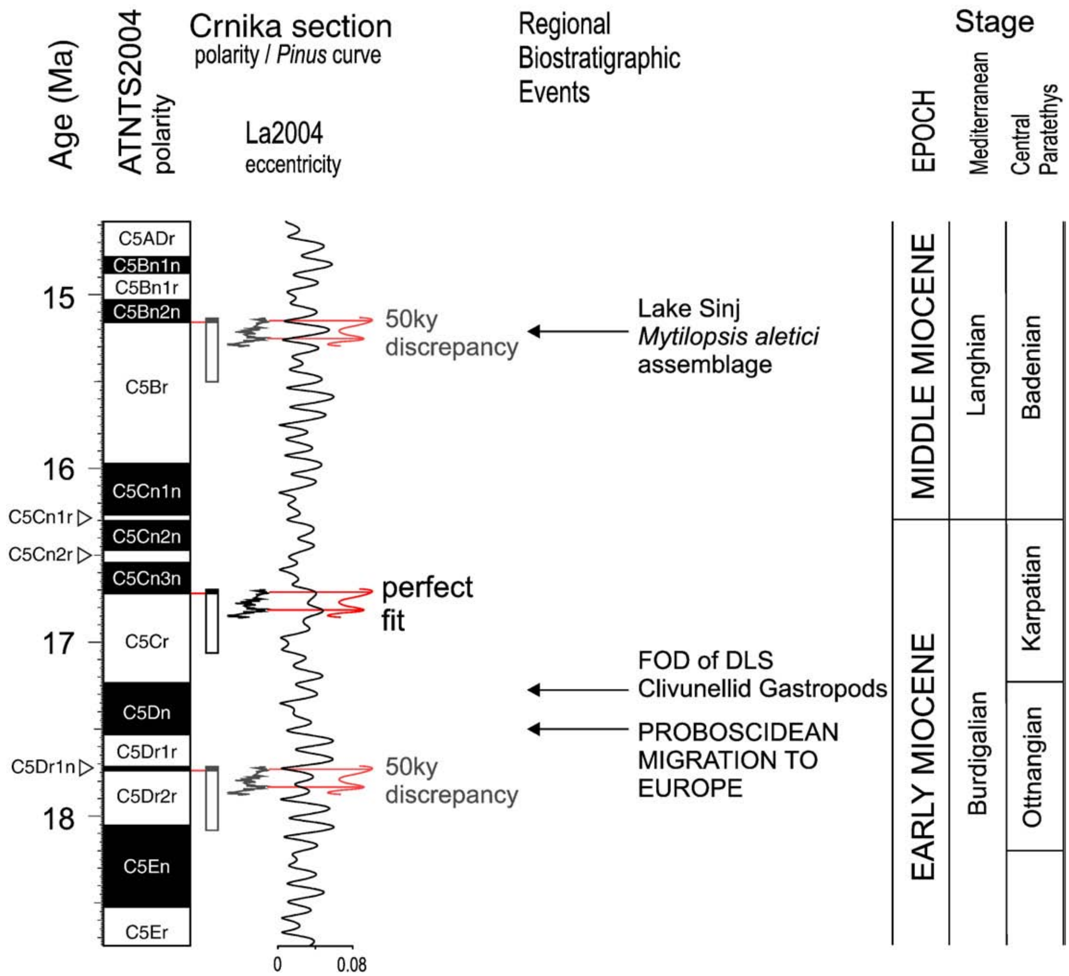


Fig. 9. Age inference for the Crnika Section on the basis of regional biostratigraphic inferences, the constructed magnetostratigraphy, and correlation of the sedimentary and palynological cyclicity to the eccentricity curve. The presence of clivunellid gastropods and the absence of highly evolved dreissenids from the *M. aletici*-group pinpointed its position to the uppermost Burdigalian. DLS: Dinaride Lake System, FOD: First Occurrence Datum. Geological Time Scale after Gradstein et al. (2004).

2) a broad-leaved evergreen forest, from sea level to around 700 m in altitude (Wang, 1961), depicted by Arecaceae, Myrica, Cyrillaceae–Clethraceae, Distylium, Castanopsis, Sapotaceae, Rutaceae, Mussaenda, Ilex, Olea, Hamamelidaceae and Engelhardia;
3) an evergreen and deciduous mixed forest above 700 m in altitude (Wang, 1961), characterized by deciduous Quercus, Engelhardia, Platycarya, Carya, Fagus, Liquidambar, Carpinus, Celtis and Acer;
4) a mid-altitude (above 1000 m (Wang, 1961)) deciduous and coniferous mixed forest with Betula, Fagus, Pinus, Cathaya and Cedrus.

Previous studies of the micro- and macrofloras from Miocene lacustrine sediments from the DLS in Croatia (Kerner, 1905a,b; Brusina, 1906, 1907; Kerner, 1916a; Bužek, 1982; Žagar-Sakač and Sakač, 1987; Šušnjara and Sakač, 1988; Jurišić-Polšak et al., 1993; Krizmanić, 1995; Pavelić et al., 2001; Meller and Bergen, 2003; Jiménez-Moreno et al., 2008b) show a flora dominated by swampy (mainly *Taxodium*-type), riparian, thermophilous and mesothermic plants indicative of a vegetation that is qualitatively very similar to the Crnika section. The main differences with the previous works (synthesis in Jiménez-Moreno, 2005) are the high abundance of *Engelhardia* (sometimes higher than 30%) and Mediterranean plants in the Crnika succession. Our pollen spectra further show very low occurrences of *Quercus* deciduous type (always below 5%). This indicates a very low representation of one of the main components of the deciduous temperate forest (deciduous *Quercus*) and a high presence of *Engelhardia*, a semi-evergreen subtropical species typical of the broad-leaved evergreen forest (Wang, 1961) and of the swamp vegetation (*Taxodium*-type) in this area.

The high abundance of Mediterranean xeric plants in Croatia during the Early (this study) and Middle Miocene (Jiménez-Moreno et al., 2008b) indicates the presence of “pre-Mediterranean” sclerophyllous vegetation. Similar high percentages of *Olea* and *Quercus ilex-coccifera* type are found in Spain and S France in the same time interval (Bessedik, 1985; Jiménez-Moreno, 2005), which may indicate similar climatic conditions in southern Europe at that time. This is markedly different from the Miocene floras of central and northern European latitudes, where those taxa are rarely found (Jiménez-Moreno, 2005).

5.3. Sedimentary cyclicity and astronomical forcing

The depositional environment in the upper part (66.7–120 m) of the Crnika section shows a progressive shallowing trend (Fig. 3). This shallowing trend includes two smaller-scale shallowing-upward cycles, from relatively deep lake conditions at the base, deduced from the deposition of organic-poor light marls and limestones with scattered *Pisidium* shells, to shallow lake/swamp conditions at the top, characterized by the deposition of coquinas dominated by shallow water *Mytilopsis* and by abundant lignites at the top of the section (Fig. 3).

The palynological results from Crnika also show two large-scale vegetation cycles, characterized by the alternation of dominantly thermophilous-xeric plants with abundant conifers (Fig. 8). The

Please cite this article as: Jiménez-Moreno, G., et al., Integrated stratigraphy of the Early Miocene lacustrine deposits of Pag Island (SW Croatia): Palaeovegetation and environmental changes..., Palaeogeography, Palaeoclimatology, Palaeoecology (2009), doi:10.1016/j.palaeo.2009.05.018

upslope or downslope movement of plant species, as recorded in percentage variations of thermophilous taxa (warm and low elevation indicators) and mid- and high-altitude conifers (cold and high elevation indicators), can be good proxies for temperature change, because vegetation is primarily sensitive to temperature and length of the growing season. This relationship has been used before in several studies that show an influence of astronomical (Milankovitch) climatic forcing on the vegetation in pollen records of the Pliocene and Miocene (Combourieu-Nebout and Vergnaud-Grazzini, 1991; Bertini, 2001; Popescu, 2001; Jiménez-Moreno et al., 2005; Jiménez-Moreno, 2006; Kloosterboer-van Hoeve et al., 2006; Popescu et al., 2006; Jiménez-Moreno et al., 2007b, 2008b).

Our study shows that fluctuations in the pollen record (see pollen zonation above; Fig. 7) seem to correlate well with sedimentological changes (Fig. 8). Therefore, the environmental change observed by the sedimentology is interpreted here to be related to the warming and possibly drying trend observed in the pollen record (Fig. 8). We interpret the significant variations in depositional environment within the Crnika section as climatically driven, producing ecological changes and lake level variations. The sedimentological variations are generally synchronous with changes in thermophilous and mid- and high-altitude pollen taxa, which most likely represent changes in broad-leaved evergreen and deciduous mixed forest and a mid-altitude coniferous forest (Figs. 7 and 8). Increases in thermophilous, T/P ratios and xeric pollen (pollen zones Pag-2 and Pag-4), likely indicating a warming- and drying-induced upslope displacement of broad-leaved evergreen forest, are generally associated with the frequent deposition of coquinas and lignites in the basin (Figs. 3 and 8), denoting periods of low lake levels and geological evidence of peat-forming paludal swampy conditions. Conversely, decreases in thermophilous pollen and T/P ratios and increases in pollen originating from a higher elevation conifer forest (pollen zones Pag–Pag-1 and Pag-3; Figs. 7 and 8) likely indicate a downslope displacement of this vegetation belt. These periods are generally associated with the deposition of deep littoral organic-poor marls and marly limestones (Figs. 3 and 8). We interpret this as periods of high lake levels during cool-humid periods.

The observed cyclicity in the vegetation and sedimentation patterns of the Crnika section is likely related to orbital variations in summer insolation, controlling cool–warm cycles and effective precipitation, which in turn influenced lake levels and vegetation in SW Croatia. This climatic interpretation of the cyclic palaeoecological and sedimentological changes coincides with several authors who demonstrated that, when cyclical alternation of lignites and organic-poor sediments (clays or marls) is observed, the deposition of lignites (in northwestern Greece: Kloosterboer-van Hoeve, 2000; Kloosterboer-van Hoeve et al., 2006; in southwestern Romania: Popescu, 2001; Popescu et al., 2006; and in Turkey: Inci, 1998) principally occurred during warm climatic phases and low lake levels, favoring the development of paludal and swampy conditions. These studies also show that the deposition of the organic-poor clays and marls took place during colder and moist periods, during higher water levels.

Vugt et al. (2001) suggested that detritic–lignite basins dominantly express eccentricity in their lithological cycles. Indeed, the two cycles documented in the upper part of the Crnika Section can be interpreted to represent the expression of the ~100 kyr eccentricity cycle, with the shallow lake/warm climate intervals reflecting periods of maximum eccentricity (Fig. 8). This assumption is in good agreement with the correlation of the palaeomagnetic reversal to chron C5Cr(y) at 16.72 Ma (Fig. 9). This reversal occurs just above the main coal layer and coincides exactly with a maximum in the eccentricity curve (Laskar et al., 2004). In the Crnika section, this interval corresponds to one of the two intervals with maximum paludal and swampy conditions. Consequently the measured distance to the other warm/shallow lake interval of about 32 m would correspond to one 100 kyr interval resulting in a sedimentation rate of 0.32 m per thousand years, which fits well into the range of lacustrine sedimentation rates presented by Cohen (2003). Moreover, as demonstrated in Fig. 9, correlations to C5Dr and C5Br imply misfits with the eccentricity curve of approximately 50 ky.

5.4. Early Miocene climate in the Dinaride Lake system

The general high amount of thermophilous plants in the Crnika pollen record suggests a warm, subtropical climate during the Early Miocene in the Pag area. The climate was also generally quite humid, necessary to support the development of a large association of hygrophilous elements that requires humid conditions all year long (Wang, 1961). Nevertheless, the presence of some xerophilous plants such as *Olea*, evergreen-*Quercus* (*Quercus ilex-coccifera* type) and Caesalpiniaceae could either indicate certain seasonality in the precipitation (and perhaps the early presence of a Mediterranean-like climate rhythm) or a xerophilous, azonal vegetation type (Utescher et al., 2007; Jiménez-Moreno et al., 2008b). This study supports previous studies (Suc, 1984; Bessedik, 1985; Quézel and Médail, 2003; Jiménez-Moreno, 2005) showing that extant typical Mediterranean plants seem to have a tropical–subtropical Neogene origin, particularly those plants living today at low elevations (thermo-Mediterranean vegetation belt) in the Mediterranean area (i.e. *Olea*).

The reason why the flora investigated in this study contains more thermophilous and xerophylous plants than other floras from Central and Northern Europe is probably related to the southern palaeogeographic location of Croatia during the Miocene, coinciding with the previous observation by Utescher et al. (2007) in the floras from Serbia. This could then point to the existence of a climatic gradient between the Dinarids and northern Europe, similar to the gradient identified in pollen records from Western Europe (from southern Spain to Switzerland; Jiménez-Moreno and Suc, 2007).

The progressive increase in thermophilous plants, T/P ratios and Mediterranean plants, in the Crnika section (Fig. 8), also observed in the sedimentology by a progressive shallowing trend, points to a warming–drying trend during the Early Miocene in this area. The warming trend could be related to the onset of the Miocene Climatic Optimum during the late Early Miocene (Zachos et al., 2001; Shevenell et al., 2004). Our pollen results are in accordance with other palaeobotanical data from Central and Southeastern Europe that also indicate thermophilous floras and high temperature estimations for the Early and early Middle Miocene (e.g. from Austria: Harzhauser et al., 2002; Hungary: Jiménez-Moreno et al., 2005; Jiménez-Moreno, 2006; Erdei et al., 2007; Germany: Mosbrugger et al., 2005; Böhme et al., 2007; Bulgaria: Ivanov et al., 2002, 2007; Bosnia–Herzegovina: Pantić and Bešlagić, 1964; Croatia: Jurišić-Polšak et al., 1993; Krizmanić, 1995; Jiménez-Moreno et al., 2008b; Serbia: Utescher et al., 2007).

6. Conclusions

The abundance of thermophilous and hygrophilous plants in the Early Miocene pollen spectra from the Crnika section on Pag Island (Dinaride Lake System, SW Croatia) indicates that the climate was subtropical and generally humid. The progressive increase in thermophilous and Mediterranean plants in the studied sequence points to a warming–drying trend during the Early Miocene in this area. This is also supported by sedimentological observations, which show progressive shallowing of the lake facies. The current age constraints imply that this warming trend could be related to the onset of the Miocene Climatic Optimum during the late Early Miocene. The pollen record from Lake Pag also documents two cyclic variations in thermophilous–xerophylous indicators and *Pinus* and other conifers, suggesting successive migrations of the surrounding vegetation belts. These fluctuations co-vary with changes in the sedimentation,

Please cite this article as: Jiménez-Moreno, G., et al., Integrated stratigraphy of the Early Miocene lacustrine deposits of Pag Island (SW Croatia): Palaeovegetation and environmental changes..., Palaeogeography, Palaeoclimatology, Palaeoecology (2009), doi:10.1016/j.palaeo.2009.05.018

denoting changes in lake level. These coeval changes in vegetation and sedimentation were most likely forced by climatic cycles. Frequent deposition of coquinas and lignites probably occurred during periods of warmer and drier climate, while the deposition of organic-poor limestones occurred during periods of cooler and wetter climate. We suggest that the observed cyclicity is related to orbital variations in summer insolation, controlling cold–warm cycles and effective precipitation, which in turn influenced lake levels and vegetation in the Pag area during the Early Miocene. It has been demonstrated that the detected lithological and vegetational cycles most likely represent expression of 100 kyr eccentricity. Magnetostratigraphic dating of the Crnika section, combined with biostratigraphic and cyclostratigraphic constraints, indicates that the lacustrine deposits of Lake Pag in the NW part of the DLS were probably deposited during the time interval between 17.2 and 16.7 Ma.

Acknowledgements

GJM's research was financed by the research grant CGL-2007-60774 by the Spanish Ministry of Science and Education. The study represents a partial result of the Austrian FWF Project P18519-B17: “Mollusk Evolution of the Neogene Dinaride Lake System” and Republic of Croatia, Ministry of Science, Education and Sports Project No. 195-1951293-2703: “Neogene terrestrial environments of the Pannonian basin and karst region”. The paleomagnetic study was supported by the Netherlands Research Centre for Integrated Solid Earth Sciences (ISES) and by the Netherlands Geosciences Foundations (ALW) with financial aid from the Netherlands Organization of Scientific Research (NWO). We thank the Editor, Jean-Pierre Suc and Torsten Utescher for their thoughtful reviews. Iuliana Vasiliev (University of Utrecht) is acknowledged for her assistance with the rock-magnetic measurements and interpretations. Our sincere thanks go to Raymond Bernor (Howard University, Washington, US) for bringing the section to our attention. We are thankful to Jeronim Bulić for guiding us in the field during the initial fieldwork and to Zlata Jurišić-Polšak and Jakov Radovčić (all Croatian Natural History Museum, Zagreb) for firsthand information about previous investigation on the section. Furthermore we are indebted to Franz Topka (NHM, Vienna) for helping us with field and laboratory work. Jodi Eckart is thanked for kindly editing the English. The last but not least our cordial thanks go to Stjepan Ćorić (Geological Survey Vienna) and Fred Rögl (NHM Vienna) for kindly checking the samples for the presence of Miocene calcareous nannoplankton and foraminifera.

References

Axelrod, D.I., Al-Shehbaz, I., Raven, P., 1996. History of the modern flora of China. In: Zhang, Aoluo, Wu, Sugong (Eds.), Floristic Characteristics and Diversity of East Asian Plants. Springer-Verlag, Berlin, pp. 43–55.

Behlilović, S., Muftić, M., 1966. Geologija Bijelog polja kod Mostara. Geološki glasnik 11, 78–102.

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.

Bessedik, M., 1985. Reconstitution des environements Miocenes des regions nord-ouest Mediterraneennes à partir de la palynologie. Ph. D. Thesis. University Montpellier 2, France, 162 pp.

Böhme, M., Bruch, A., Selmeier, A., 2007. The reconstruction of Early and Middle Miocene climate and vegetation in Southern Germany as determined from the fossil wood flora. Palaeogeogeography, Palaeoclimatoloy, Palaeoecology 253, 91–114.

Brusina, S., 1906. Naravoslovne crtice sa sjeveroiztočne obale Jadranskoga more. III Putopis. Rad Jugoslavenske akademije znanosti i umjetnosti 163, 1–40.

Brusina, S., 1907. Naravoslovne crtice sa sjeveroiztočne obale Jadranskoga more. Dio cetvrti i posljednji. Rad Jugoslavenske akademije znanosti i umjetnosti 169, 195–251.

Bužek, C., 1982. *Ceratostratiotes* Gregor, an extinct water plant of uncertain affinity from the European Miocene. Vestnik Ustredniho Ustavu Geologickeho 57 (5), 285–294.

Cohen, A.C., 2003. Palaeolimnology. The History and Evolution of Lake Systems. InOxford University Press, New York. pp. i–ix + 1–500.

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.

Ćorić, S., Babić, Lj., Hernitz-Kučenjak, M., Zupanič, J., 2008. Conflicting dating of the coastal Dinaric flysch, and implications: Eocene or Miocene? The Case of North Dalmatia and Istria: Geophysical Research Abstracts, vol. 10. EGU2008-A-07305.

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.

Engelhard, H., 1883. Über bosnische Tertiärpflanzen. Beschreibung einiger Tertiärpflanzen von Bijelo Brdo bei Višegrad in Bosnien. Ges. “Isis” in Dresden 11, 85–88.

Engelhard, H., 1900. Über Tertiärpflanzen aus Bosnien. Verhandlungen der k.u.k. Geologischen Reichsanstalt 1900, 187–189.

Engelhard, H., 1901. Prilog poznavanju tercijarne flore najšire okoline Donje Tuzle u Bosni. Glasnik Zemaljskog Muzeja u Bosni i Hercegovini 13, 473–526.

Engelhard, H., 1902a. Verzeichnis der im Jahre 1901 in Bosnien und Hercegowina aufgefundenen Tertiärpflanzen. Verhandlungen der k.u.k. Geologischen Reichsanstalt 142–143.

Engelhard, H., 1902b. Prilog poznavanju tercijarne flore Bosne i Hercegovine. Glasnik Zemaljskog Muzeja u Bosni i Hercegovini 14, 441–460.

Engelhard, H., 1903. Prilog poznavanju fosilne flore iz naslaga smeđeg ugljena u kotlini Zenica–Sarajevo u Bosni. Glasnik Zemaljskog Muzeja u Bosni i Hercegovini 15, 115–148.

Engelhard, H., 1904a. Prilog poznavanju tercijarne flore okoline Prozora. Glasnik Zemaljskog Muzeja u Bosni i Hercegovini 16 (4), 245–262.

Engelhard, H., 1904b. Tercijarne bilinene iz Foče na jugoistoku Bosne. Glasnik Zemaljskog Muzeja u Bosni i Hercegovini 16, 555–562.

Engelhard, H., 1910. Novi prilozi poznavanju tercijarne flore Bosne. Glasnik Zemaljskog Muzeja u Bosni i Hercegovini 22, 141–172.

Engelhard, H., 1912. K poznavanju tercijarne flore sjeverozapadne Bosne. Glasnik Zemaljskog Muzeja u Bosni i Hercegovini 24, 515–524.

Engelhard, H., 1913. Novi prilog poznavanju tercijarne flore Bosne. Glasnik Zemaljskog Muzeja u Bosni i Hercegovini 25, 383–396.

Erdei, B., Hably, L., Kázmér, M., Utescher, T., Bruch, A.A., 2007. Neogene flora and vegetation development of the Pannonian domain in relation to palaeoclimate and palaeogeography. Palaeogeography, Palaeoclimatology, Palaeoecology 253, 115–140.

Gradstein, F.M., Ogg, J.G., Smith, A.G., 2004. A Geologic Time Scale 2004. InCambridge University Press, pp. 1–610.

Grimm, E., 1993. Tilia and Tilia graph versions 2.o.b.4. Illinois State Museum, Research and Collections Center.

Harzhauser, M., Mandic, O., 2008a. Neogene lake systems of Central and South-Eastern Europe: faunal diversity, gradients and interrelations. Palaeogeography, Palaeoclimatology, Palaeoecology 260/3–4, 417–434.

Harzhauser, M., Mandic, O., 2008b. Neogene Dreissenids in Central Europe — exploring the limits. In: Van der Velde, G., Rajagopal, S., Bij de Vaat, A. (Eds.), Zebra Mussels in Europe.

Harzhauser, M., Böhme, M., Mandic, O., Hofmann, Ch.-Ch., 2002. The Karpatian (Late Burdigalian) of the Korneuburg Basin — A palaeoecological and biostratigraphical synthesis. Beiträge zur Paläontologie 27, 441–456.

Inci, U., 1998. Lignite and carbonate deposition in Middle Lignite succession of the Soma Formation, Soma coalfield, western Turkey. International Journal of Coal Geology 37, 287–313.

Ivanov, D., Ashraf, A.R., Mosbrugger, V., 2007. Late Oligocene and Miocene climate and vegetation in the Eastern Paratethys area (northeast Bulgaria), based on pollen data. Palaeogeography, Palaeoclimatology, Palaeoecology 255, 342–360.

Ivanov, D., Ashraf, A.R., Mosbrugger, V., Palmarev, E., 2002. Palynological evidence for Miocene climate change in the Forecarpathian Basin (Central Paratethys, NW Bulgaria). Palaeogeography, Palaeoclimatology, Palaeoecology 178, 19–37.

Jiménez-Moreno, G., 2005. Utilización del análisis polínico para la reconstrucción de la vegetación, clima y palaeoaltitudes a lo largo del arco alpino europeo durante el Mioceno (21–8 Ma). Ph.D. Thesis disertation. Universidad de Granada, Granada, Spain.

Jiménez-Moreno, G., 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 Palaeobotany and Palynology 142, 1–14.

Jiménez-Moreno, G., Suc, J.-P., 2007. Middle Miocene latitudinal climatic gradient in western Europe: evidence from pollen records. Palaeogeograhy, Palaeoclimatology, Palaeoecology 253, 224–241.

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 (1–2), 73–97.

Jiménez-Moreno, G., Fauquette, S., Suc, J.-P., Abdul-Aziz, H., 2007a. Early Miocene repetitive vegetation and climatic changes in the lacustrine deposits of the Rubielos de Mora Basin (Teruel, NE Spain). Palaeogeography, Palaeoclimatology, Palaeoecology 250, 101–113.

Jiménez-Moreno, G., Abdul-Aziz, H., Rodríguez-Tovar, F.J., Pardo-Igúzquiza, E., Suc, J.-P., 2007b. Palynological evidence for astronomical forcing in Early–Middle Miocene lacustrine deposits from Rubielos de Mora Basin (NE Spain). Palaeogeography, Palaeoclimatology, Palaeoecology 252, 601–616.

Jiménez-Moreno, G., Fauquette, S., Suc, J.-P., 2008a. Vegetation, climate and palaeoaltitude reconstructions of eastern alpine mountain ranges during the Miocene based on pollen records from Austria, Central Europe. Journal of Biogeography 35, 1638–1649.

Jiménez-Moreno, G., Mandic, O., Harzhauser, M., Pavelić, D., Vranjković, A., 2008b. Vegetation and climate dynamics during the Early Middle Miocene from Lake Sinj (Dinaride Lake System, Croatia). Review of Palaeobotany and Palynology 152, 237–245.

Jurišić-Polšak, Z., Bulić, J., 2007. Pradavno Paško jezero, pp. 1–63 (Hrvatski prirodoslovni muzej) Zagreb.

Jurišić-Polšak, Z., Krizmanić, K., Hajek-Tadesse, V., 1993. Freshwater Miocene of Krbavsko Polje in Lika (Croatia). Geologia Croatica 46 (2), 213–228.

Katzer, F., 1918. Die fossilen Kohlen Bosniens und der Hercegovina. Erster Bd. Selbstverlag, pp. 1–403.

Katzer, F., 1921. Die fossilen Kohlen Bosniens und der Hercegovina. Zweiter Bd. Verlag bosnisch-herzegowinischer geologischen Landesanstalt, pp. 1–271.

Kerner, F., 1905a. Gliederung der Sinjaner Neogen-formation. Verhandlungen der k.u.k. Geologischen Reichanstalt 1905 (6), 127–165.

Kerner, 1905b. Neogenpflanzen vom Nordrande des Sinjsko polje in Mitteldalmatien. Jahrbuch der k.u.k. Geologischen Reichsanstalt 55 (3–4), 593–612.

Kerner, F., 1916a. Alt- und jungtertiäre Pflanzenreste aus dem obersten Cetinatale. Verhandlungen der k.u.k. Geologischen Reichanstalt 1916 (8), 180–191.

Kirschvink, J.L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data. Geophysical Journal International 62 (3), 699–718.

Kloosterboer-van Hoeve, M.L., 2000. Cyclic changes in the Late Neogene vegetation of northern Greece, a palynological study. PhD Thesis, Utrecht, 132 pp.

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.

Kochansky-Devidé, V., Slišković, 1972. Revizija roda Clivunella Katzer, 1918 i Delminella n.gen. (Gastropoda). Geološki glasnik 16, 47–70 Sarajevo.

Kochansky-Devidé, V., Slišković, T., 1978. Miocenske Kongerije Hrvatske, Bosne i Hercegovine. Palaeontologia Jugoslavica 19, 1–98.

Kochansky-Devidé, V., Slišković, T., 1980. Mlađe Miocenske Kongerije Livanjskog, Duvanjskog i Kuprеškog Polja u jugozapadnoj Bosni i Hodova u Hercegovini. Palaeontologia Jugoslavica 25, 1–25.

Krizmanić, K., 1995. Palynology of the Miocene bentonite from Gornja Jelenska (Mt. Moslavačka Gora, Croatia). Geologia Croatica 48 (2), 147–154.

Krstić, N., Savić, Lj., Jovanović, G., Bodor, E., 2003. Lower Miocene lakes of the Balkan Land. Acta Geologica Hungarica 46 (3), 291–299.

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M., Levrard, B., 2004. A long term numerical solution for the insolation quantities of the Earth. Astronomy and Astrophysics 428, 261–285.

Mamužić, P., Sokač, B., 1967. Tumač za listove Silba i Molat. Osnovna geološka karta 1:100000. p. 45, Savezni geološki zavod, Beograd.

Mamužić, P., Sokač, B., Velić, I., 1970. Osnovna geoloska karta SFRJ, List Molat L 33–138 i Silba L 33–126. 1:100.000. Geološki zavod Zagreb, Savezni geološki zavod Beograd.

Mandic, O., Harzhauser, M., Pavelić, D., de Leeuw, A., Krijgsman, W., 2007. An integrative study of lacustrine successions of the Sinj Basin (Miocene Dinaride Lake System, SE Croatia) — palaeontology, depositional history, cyclostratigraphy and palaeomagnetics. Geophysical Research Abstracts 9, 10331.

Mandic, O., Pavelić, D., Harzhauser, M., Zupanič, J., Reischenbacher, D., Sachsenhofer, R.F., Tadej, N., Vranjković, A., 2009. Depositional history of the Miocene Lake Sinj (Dinaride Lake System, Croatia): a long-lived hard-water lake in a pull-apart tectonic setting. Journal of Palaeolimnology 41, 431–452.

Meller, B., Bergen, P.F.v., 2003. The problematic systematic position of *Ceratostriatus* Gregor (Hydracharitaceae?) — morphological, anatomical and biochemical comparison with *Stratiotes* L. Plant Systematics and Evolution 236, 125–150.

Mosbrugger, V., Utescher, T., Dilcher, D.L., 2005. Cenozoic continental climatic evolution of Central Europe. Proceedings of the National Academy of Sciences of the United States of America 102, 14964–14969.

Muftić, M., 1964. Prilog geološkom poznavanju gatačkog ugljenonosnog bazena. Geološki glasnik 9, 139–154.

Muftić, M., 1970. Ugljenonosne naslage Banjaluke. Geološki glasnik 14, 203–216.

Muftić, M., Behlilović, S., 1961. Prikaz geološkog poznavanja ugljonosnih naslaga Gračanice kod Bugojna. Geološki glasnik 11, 303–312.

Muftić, M., Lubunć, P., 1963. Prilog poznavanju litostratigrafskih i tektonskih odnosa jezerskog neogena u Bosni i Hercegovini. Geološki glasnik 7, 103–130.

Palfy, J., Mundil, R., Renne, P.R., Bernor, R.L., Kordos, L., Gasparik, M., 2007. U–Pb and 40Ar/39Ar dating of the Miocene fossil track site at Ipolytarnóc (Hungary) and its implications. Earth and Planetary Science Letters 258, 160–174.

Pantić, N., 1957. Fitostratigrafija tercijarnih flora SI Bosne. Zbornik II Kongresa geologa FNRJ, Sarajevo.

Pantić, N., 1961. O starosti slatkovodnog tercijara sa ugljem u Bosni na osnovu palaeofloristickih istrazivanja. Geološki anali Balkanskog poluostrva 28, 1–22.

Pantić, N., Bešlagić, A., 1964. Palinološke analize mrkog uglja i lignita iz Livanjskog tercijarnog bazena. Geološki anali Balkanskog poluostrva 31, 127–132.

Pantić, N., Ercegovac, M., Pantić, V., 1966. Palinološka ispitivanja i stratigrafija terestrično-limničkih tercijarnih naslaga u Zeničko–Sarajevskom basenu. Geološki anali Balkanskog poluostrva 32, 183–210.

Pavelić, D., Avanić, R., Bakrač, K., Vrsaljko, D., 2001. Early Miocene braided river and lacustrine sedimentation in the Kalnik mountain area (Pannonian Basin System, NW Croatia). Geologica Carpathica 52 (6), 375–386.

Pike, C.R., Roberts, A.P., Verosub, K.L., 2001. First-order reversal curve diagrams and thermal relaxation effects in magnetic particles. Geophysical Journal International 145 (3), 721–730.

Polić, A., 1935. O Oligocenu i njegovoj flori kod Planine u Zagrebačkoj gori. Rad JAZU, 251, Mat. prir.razr. 78, Zagreb.

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. Palaeogeography, Palaeoclimatology, Palaeoecology 238, 340–348.

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

Radimsky, O., 1877. Über den geologischen Bau der Insel Pago. In: Verhandlungen der k. u.k. geologischen Reichsanstalt. Wien. 1877.

Roberts, A.P., Pike, C.R., Verosub, K.L., 2000. First-order reversal curve diagrams: a new tool for characterizing the magnetic properties of natural samples. Journal of Geophysical Research 105/B12, 28461–28476.

Shevenell, A.E., Kennett, J.P., Lea, D.W., 2004. Middle Miocene Southern Ocean cooling and Antartic cryosphere expansion. Science 305, 1766–1770.

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

Šušnjara, A., Sakač, K., 1988. Miocene freshwater sediments of the Sinj area — Middle Dalmatia. Geološki vjesnik 41, 51–74.

Tari, V., 2002. Evolution of the northern and western Dinarides: a tectonostratigraphic approach. European Geosciences Union Stephan Mueller Special Publication Series 1, 223–236.

Thompson, J.D., 2005. Plant evolution in the Mediterranean. Oxford University Press.

Utescher, T., Djordjevic-Milutinovic, D., Bruch, A.A., Mosbrugger, V., 2007. Palaeoclimate and vegetation change in Serbia during the last 30 Ma. Palaeogeography, Palaeoclimatology, Palaeoecology 253, 141–152.

Vasiliev, I., Franke, C., Meeldijk, J.D., Dekkers, M.J., Langereis, C.G., Krijgsman, W., 2008. Putative greigite magnetofossils from the Pliocene epoch. Nature Geoscience 1 (11), 782–786.

Vasiliev, I., Dekkers, M.J., Krijgsman, W., Franke, C., Langereis, C.G., Mullender, T.A.T., 2007. Early diagenetic greigite as a recorder of the palaeomagnetic signal in Miocene–Pliocene sedimentary rocks of the Carpathian foredeep (Romania). Geophysical Journal International 171, 613–629.

Vasković, D., 1931. Einige neue Pflanzenreste von Kakanj, Breza und Vogošća bei Sarajevo. Glasnik Zemaljskog muzeja Sarajevo.

Veen, F.R, van, 1954. Pollenuntersuchungen an Braunkohle aus Breza und Tusnica. Glasnik Biološkog Instituta Sarajevo 7 (1–2).

Vugt, N. van, Langereis, C.G., Hilgren, F.J., 2001. Orbital forcing in Pliocene–Pleistocene Mediterranean lacustrine deposits: dominant expression of eccentricity versus procession. Palaeogeography, Palaeoclimatology, Palaeoecology 172, 193–205.

Wang, C.W., 1961. The forests of China with a survey of grassland and desert vegetation. Maria Moors Cabot Fundation, vol. 5. Harvard University, Cambridge, Massachusetts.

Weyland, H., Pflug, H., Pantić, N., 1958. Untersuchungen über die Sporen und Pollen-Flora einige jugoslawischer und griechischer Braunkohlen. Palaeontographica, Abteilung B 105.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292, 686–693.

Žagar-Sakač, A., Sakač, K., 1987. Novi nalazi fosilnih lopoča (Nymphaeaceae) u tercijarnim naslagama Dalmacije. Rad Jugoslavenske akademije znanosti i umjetnosti, 431, Razred prirodnih znanosti 22, 207–218.

Zijderveld, J.D.A., 1967. A.c. demagnetisation of rocks: analysis of results. Methods in Palaeomagnetism. InElsevier, Amsterdam, pp. 254–286.