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Vegetation and climate dynamics during the early Middle Miocene from Lake Sinj (Dinaride Lake System, SE Croatia)

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ABSTRACT

Pollen data from sediments from an outcrop section in the ancient Lake Sinj (Dinaride Lake System, SE Croatia) record variations in vegetation during the early Middle Miocene. Good correspondence between the palaeo-vegetation and the sedimentological profile suggests that both records are mainly controlled by variations in the past climatic conditions. Periods of frequent coal deposition generally coincide with high abundance of thermophilous and xeric indicators suggesting warm and dry climate. Pollen and sediment records show two large-scale warming and shallowing-upward cycles and smaller-scale cyclicity. The high relative percentage of warm pollen taxa in the entire record, with *Engelhardia* as the main component, generally indicates a subtropical humid climate for this area during the early Middle Miocene, probably related to the Miocene Climatic Optimum. This study shows a response of the vegetation to climate change at short-term, probably related to orbital cyclic variations in summer insolation during the Middle Miocene.

1. Introduction

The Dinaride Lake System (DLS) is a tectonically induced series of coal coal-bearing basins that are characterized during the Miocene by lacustrine sedimentation (Fig. 1). Up to the end of the Early Miocene, the DLS also included the southern Pannonian Basin System, being subsequently flooded by a marine transgression during the Middle Miocene. The DLS is punctually fairly rich in plant macrofossils and the investigations of its extensive coal deposits in Bosnia and Herzegovina resulted in a number of publications describing and interpreting the palaeobotanical record (Engelhardt, 1883, 1900, 1901, 1902a,b, 1903, 1904a,b, 1910, 1912, 1913; Katzer, 1918, 1921; Vasković, 1931; Van Veen, 1954; Pantić, 1957, 1961; Weyland et al., 1958; Muftić and Behlilović, 1961; Muftić and Luburić, 1963; Pantić and Bešlagić, 1964; Muftić, 1964, 1970; Behlilović and Muftić, 1966; Pantić et al., 1966).

Southern areas of Europe such as the Balkans are very interesting from the floristic point of view due to the presence of Miocene, Pliocene and Pleistocene relics in their present-day floras (Quézel and Médail, 2003; Thompson, 2005). Mostly because of their geographical situation, these areas served as a refuge for mostly thermophilous plants that otherwise would have vanished from Eurasia during the Pleistocene glaciations (Quézel and Médail, 2003). Previous palaeobotanical studies from Serbia also show that during the Miocene, the floristic composition of the palaeofloras in the Balkan Peninsula differs from other Miocene floras from Central and Western Europe (Utescher et al., 2007). This particular flora was explained by a specific palaeogeographic situation, the geomorphological evolution, and the southern latitudinal position of that region during the Miocene (Utescher et al., 2007). This peculiarity of the flora from Serbia may be true for other areas of the Balkan Peninsula such as the Dinaride Mountains in Croatia and Bosnia and Herzegovina, however, in Croatia palaeobotanical studies, besides the few ones from the Sinj Basin (see below), are rare. For example, only three studies have been carried out in the DLS phase of the southern Pannonian Basin System (Polić, 1935; Krizmanić, 1995; Pavelić et al., 2001) and from the Dinaride basins and the Adria Block the information is available solely from Radimsky (1877), Jurišić-Polšak et al. (1993) and Jurišić-Polšak and Bulić (2007). Moreover, the general scarceness of quantitative information and the use of a morphometric classification of pollen grains, make comparisons with those previously documented floras very difficult. Additional difficulty is the poor stratigraphic resolution of DLS deposits with age inferences based only on palynology or scattered macromammal remains.

1.1. Previous palaeobotanical studies from the Sinj Basin (SE Croatia)

The only palynological data from the Sinj Basin were provided by Šušnjara and Sakač (1988), although there is a lack of quantitative pollen information in their study. The composition of the macroflora (mainly aquatics) and its change during the lake deposition is known in more detail (Kerner, 1905a,b, 1916a; Brusina, 1906, 1907; Buzek,

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1982, Žagar-Sakač and Sakač, 1987; Meller and Bergen, 2003). The Sinj Basin comprises type localities for several aquatic fossil plants such as a star-fruit *Damasonium sutinae* Kerner, 1905a, *Cyperites tiluri* Kerner, 1905a and a tentative tape-grass representative *Doderleinia sinjana* Kerner, 1905a. A very detailed morphologic documentation and taxonomic interpretation on the latter aquatic plant is available in Buzek (1982) and currently in Meller and Bergen (2003). Note however that *Doderleinia* Brusina, (1906) with the type species *Ceratophyllum sinjanum* Kerner (1905a) is a senior synonym of *Ceratostriotis* Gregor (1980) used by latter authors. The monotypic genus *Doderleinia* is a common constituent of the Upper Ottnangian (upper Burdigalian) deposits at the eastern margin of the Bohemian Massif in Austria and Czech Republic (Meller and Bergen, 2003). Being very common in the lower part of the basinal infill at Sinj, it seems to be completely missing in its upper part, which in contrast is characterized by mass occurrences of *D. sutinae* (Mandic et al. 2008).

The Lake Sinj macrofossil terrestrial plant assemblage is characterized in the lower sedimentary unit (Fig. 2) by the presence of *Taxodium distichum miocenicum* Herr, *Pinus* sp., *Castanea kubinyi* Kov.?, *Cinnamomum scheuchzeri* Herr, *Dryandroides lignitum* Ung. sp. and *Juglans acuminata* Al. Br. The middle and upper units are marked by the absence of *Taxodium* remains (Kerner 1905a, 1916b). The middle unit of the infill is depicted by abundant *Cyperites* and the upper part, characterized by the abundance of star-fruit remains, comprises *Pinus* sp., *Betula* sp.? *Myrsine endymionis* Ung., *Bumelia oreadum* Ung., *Diospyros lotoides* Ung., *Rhododendron* cfr. *megiston* Ung. and *Cassia hyperborea* Ung.?.

Due to the scarcity of pollen and terrestrial macrofloral studies, the vegetation and climate history of the western Balkan Peninsula still remains unclear. This pollen study will add significant palaeobotanical information from SE Croatia that will help us improve the understanding of the flora, vegetation and climate of Southeastern Europe and the Dinaride Lake System during the Miocene.

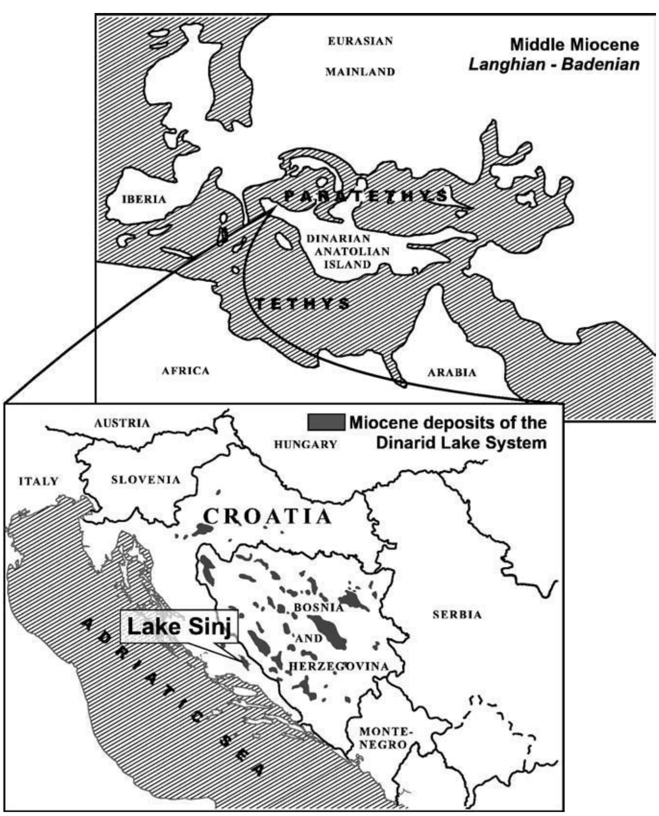

Fig. 1. Palaeogeographic and regional geological setting of the Sinj Basin (modified after Harzhauser and Mandic, 2008a).

2. Geological setting

The studied deposits are located in SE Croatia and belong to the infill of the Sinj Basin, located on the SE margin of the External Dinarides. The basin is 38 km long and 9 km wide, oriented NW–SE and it can be interpreted as a pull-apart tectonic structure. It was formed within the Western Thrust Belt of the Dinarides during the Early and Middle Miocene due to transpressional wrenching resulting from northward oblique-slip motions of the underthrusting Adriatic Block (Tari, 2002). That transpressional regime initiated numerous other synchronous NW–SE oriented pull-apart basins distributed across the Dinarides. Together, these basins accommodated a system of fresh water environments termed the Dinaride Lake System (Krstić et al., 2003; Harzhauser and Mandic 2008a,b). The Dinaride Lake System represented an independent palaeogeographic and palaeobiogeographic entity restricted to the northern part of the Dinarian–Anatolian Island, which acted as a geographic barrier between the Paratethys and the proto-Mediterranean (Fig. 1).

The succession of Miocene freshwater deposits of the Sinj Basin, dominantly consisting of limestones, coal intercalations, and a few tuff beds, was mapped and studied in detail by Kerner (1916b,c), Šušnjara and Šćavničar (1974) and Šušnjara and Sakač (1988). According to the latter authors, three main lithological units can be distinguished in the sedimentary sequence (Fig. 2). The basal unit ("Basal beds") comprises varicolored marls in the western part of the basin and "Older coal-bearing beds" and marls with dreissenids in the eastern part of the basin. This sedimentary difference was interpreted as reflecting the different lithological character of the basement rocks. Clayey limestones and limy marls throughout the basin form the middle unit. The upper unit is termed "Younger coal-bearing beds" and is mainly made up of fossiliferous limy marls containing coal intercalations (one up to 4 m thick) as well as dreissenid marl subunits. The "Younger coal-bearing beds" are especially well developed along the southwestern basinal margin, where they onlap transgressively (Šušnjara and Sakač, 1988).

Miocene lacustrine sediments from the upper unit of the basinal infill from the Sinj Basin show two large-scale shallowing shallowing-upward cycles (about 60 m each), both starting with fossil-poor limestones gradually passing into coal-bearing carbonate rocks and coal seams, respectively (Šušnjara and Sakač, 1988; Mandic et al., 2008; Fig. 2). The fossil-poor intervals have been previously interpreted as open-lake and wet-climate phases and the coal-rich intervals as marginal-lake and dry-phases (Šušnjara and Sakač, 1988; Mandic et al., 2008). These interpretations were made after a detailed study of the sedimentology, microfacies, coal petrology and fossil content (mollusks and plant remains) of the studied sequence. Previous studies then show a climatic control of the sedimentary evolution in the Sinj Basin (Šušnjara and Sakač, 1988; Mandic et al., 2008). Pollen analysis is very useful for detecting climatic fluctuations and has been carried out in a previously studied sedimentary sequence from the Sinj Basin (Mandic et al., 2008) in order to contrast the previously observed climatic hypothesis through changes on the vegetation. The quantitative analysis of the pollen data has been used to characterize the observed sedimentary cyclicity in terms of repetitive changes in vegetation and climate.

2.1. Lučane section

Mandic et al. (2008) presented a detailed analysis of the sedimentology and facies of the upper coal seam bearing part of the Lučane section. Its downward prolongation up to the basal breccias, previously mapped and described by Kerner (1905a, 1916b), was subsequently measured and sampled (Fig. 3), resulting with estimated thickness of 497.8 m down to a 5 m thick tephra layer in the base (N43 43 27.8 E16 36 43.8). The actual contact with the breccia, outcropped c. 50 m NW from there, has not been studied because of the thick Pleistocene alluvial coverage.

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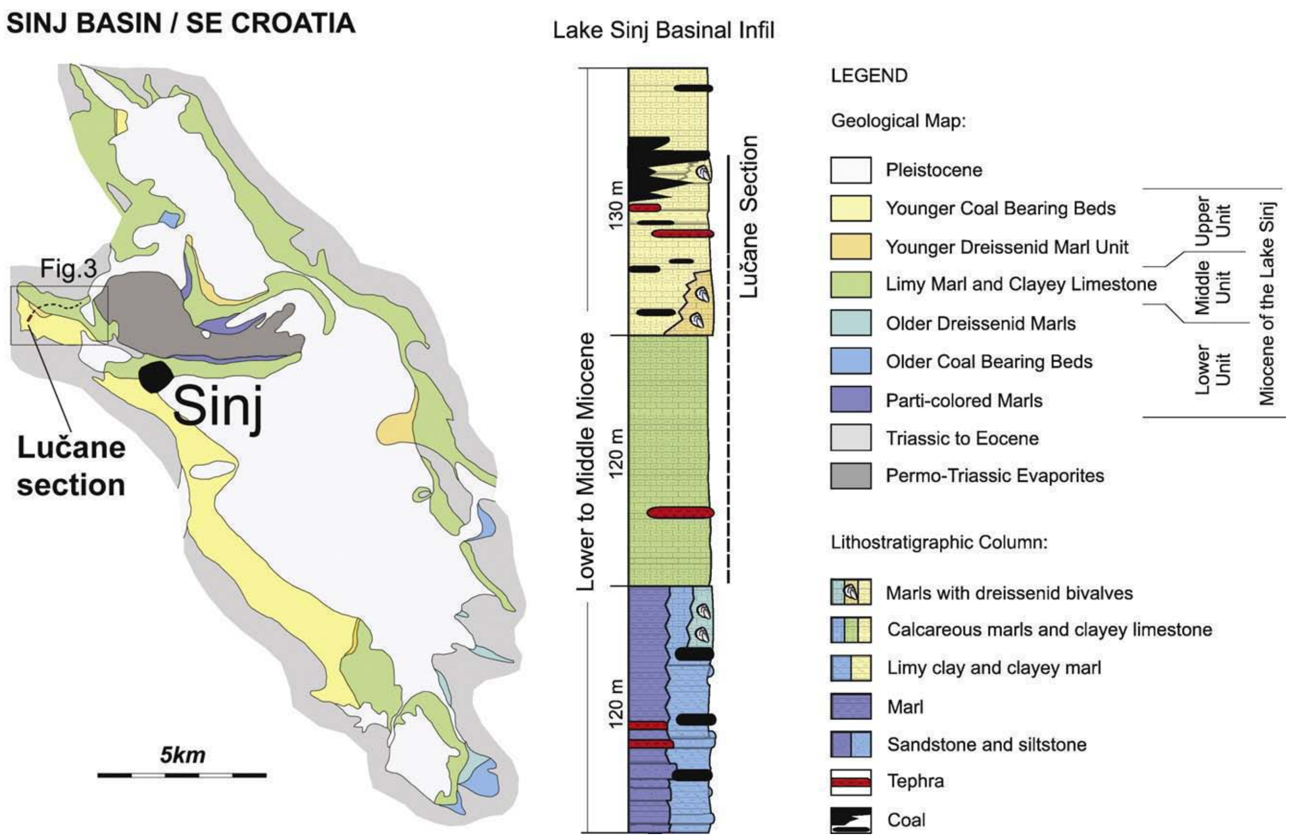

Fig. 2. Geological map of the Sinj Basin showing the classification and distribution of lithostratigraphic units of the Miocene infill (modified after Šušnjara and Sakač, 1988).

The stratigraphically lowermost pollen sample described in the present study was collected at 383.09 m (N43 43 23.0 E16 36 20.7) within the *Doderleinia sinjana* zone (Fig. 3) and from a banded marly limestone bearing fruits of the already mentioned water plant. A marly limestone succession, characterized by very poor pollen preservation follows up to the next two samples at 197.47 m (N43 43 20.0 E16 35 37.1), and 201.29 m (N43 43 19.7 E16 35 37.4) (Fig. 3). Therein, grayish limy marls with large articulated shells of the dreissenid bivalve *Mytilopsis drvarensis* Toula are interbedded by up to 1 m thick limestones. Marly limestones again dominate the following 100 m of the section. Between 146 and 158 m of the section (below the shown part of the section in Fig. 6), one single desiccation crack horizon was observed, pointing to a small-scale emersion event followed immediately by an about 20 m thick slumped, intraclast bearing unit. Those seismites indicate enhanced tectonic activity around the lake for that particular time interval.

The superposing limestones are already within the section analyzed by Mandic et al. (2008). There, the bedded fossil-poor limestones bear abundant *Damasonium sutinae* fruits pointing to the presence of a rich star-fruit monoculture at the lake rim. The cyclic flooding of that rim, implied by the presence of such plant remains in deeper littoral lake

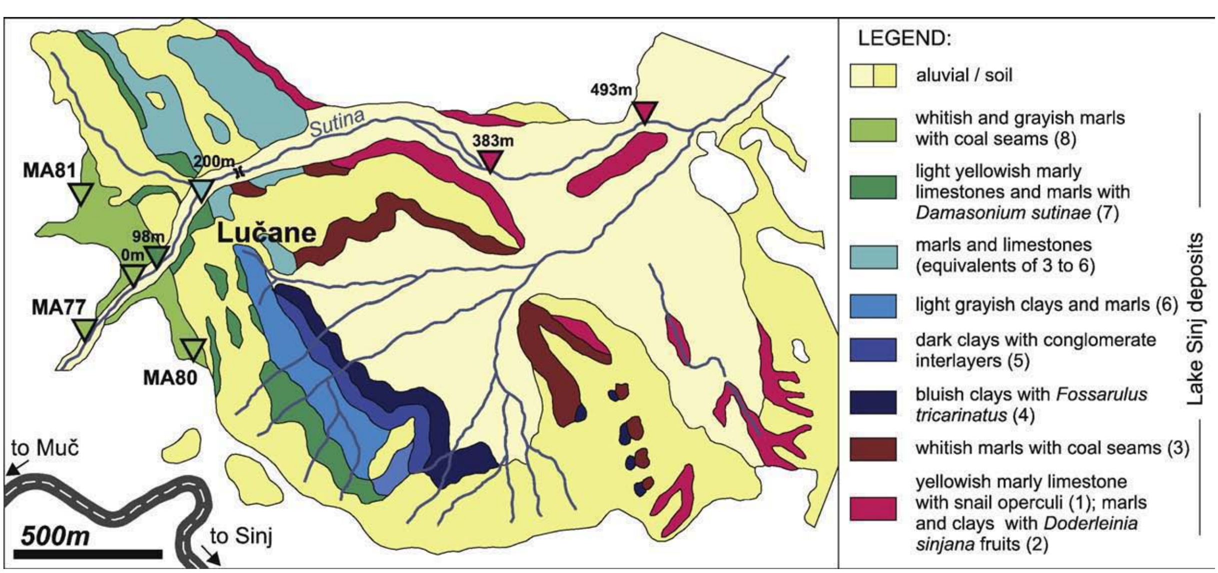

Fig. 3. Geological map of the western Sinj Basin around Lučane showing the position of the studied samples (modified after Kerner 1905a).

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deposit, could seriously affect the lake ecosystem by reoccurring acidification events (Mandic et al., 2008). The topmost part of the Lučane section is characterized by the presence of coal seam deposits in the Lake Sinj described also by Kerner (1905a) and Šušnjara and Sakač (1988) (Figs. 2, 3 and 6). That coal formation is arranged in two ca. 40 m thick large-scale cycles, intercalated by about 20 m of limestone poor in organic matter. Each cycle comprises several smaller-scale limestone/ coal interbedding phases (Fig. 6). Such architecture reflects cyclic changes of the lake level, where limestones represent open-lake environment within the photic zone and the organic-rich sediments are related to marginal-lake swamps and mires (Mandic et al., 2008). Conclusively, these authors pointed to a perennial lake environment through the studied sedimentary sequence as no palaeosols or desiccation marks are found, except for a main coal seam in the uppermost part of the section. They also showed that before its final disintegration, the ancient lake Sinj went through two superposed, large-scale, shallowing shallowing-upward depositional cycles. Each of them starting with deep littoral organic-poor limestones, then passing through shallow littoral tempestites and finally ending in the infralittoral coal/ limestone interbedding series. The latter was subdivided into several subcycles of organic enrichment that were interpreted as triggered by the short-term, orbitally forced cyclic fluctuation of humid and dry periods. The end of the upper cycle is characterized by the presence, for the first time, of high mire, indicating the complete drying up of the lake.

Additional pollen samples taken from lateral outcrops to the main section represent different intervals of the coal seam producing interval. Hence MA-77 (N43 43 04.0 E16 35 18.3) comes from the base of the section described by Olujić (1999) and Mandic et al. (2008, Fig. 14) and represents the most proximal position to the actual lake rim. Olujić (1999) correlated it with the lower cycle of the coal coal-bearing sequence (ca. 70 m) of the Lučane section. According to the geological map by the latter author, sample MA-81 (N43 43 18.9 E16 35 19.8) represents the stratigraphically youngest part of the Lučane succession that has not been cut through the main section. Its relative position to the top of the main section remains unclear. The same holds true for the sample MA-80 (N43 43 00.1 E16 35 36.6), except

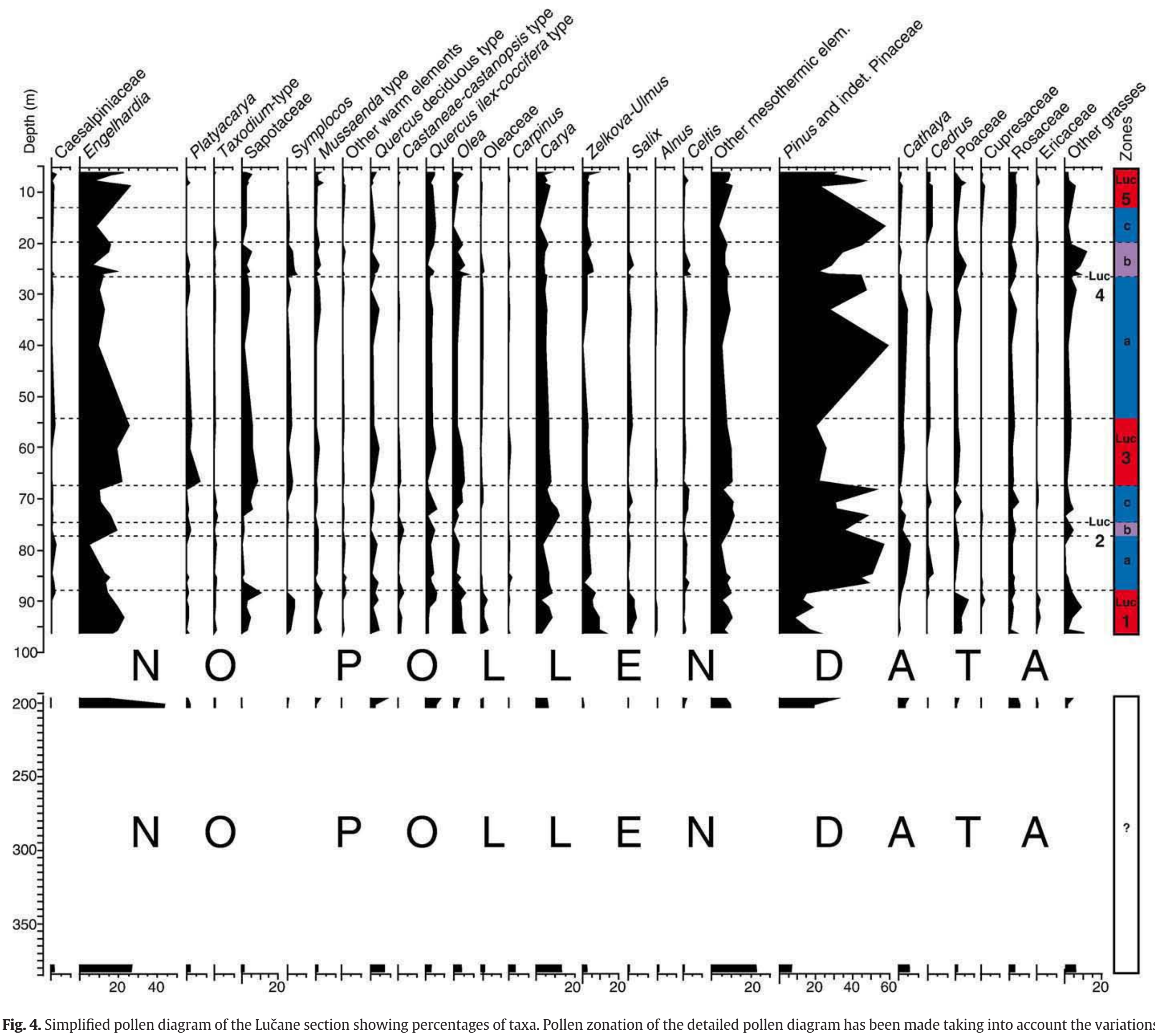

Fig. 4. Simplified pollen diagram of the Lučane section showing percentages of taxa. Pollen zonation of the detailed pollen diagram has been made taking into account the variations in relative percentage of the main taxa occurring in the studied section. Pollen zonation was only made in the upper part of the section due to very low pollen sample resolution in the lower part.

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that Olujić (1999) considered it to be older than MA-81, correlating it with the upper part of the Lučane section.

2.2. Age

The age inference for the Lake Sinj succession is based on a literature update and points to an early Langhian age (early Middle Miocene). The mammal fauna collected in the topmost coal seams of the Lučane section by mine workers in the 1930s and curated currently in the Croatian Natural History Museum in Zagreb comprises *Gomphotherium angustidens* Cuvier and *Brachypotherium brachypus* Lartet (J. Radovčić in Olujić, 1999). Their co-occurrence indicates the time interval between the latest Early Miocene and the Middle Miocene. Yet, from the same layer and collection, Bernor et al. (2004) identified subsequently remains of a primitive suid *Conochyus olujici* Bernor, Bi & Radovčić. Based on its evolutionary stage, the latter authors inferred the stratigraphic range of the layer from ca. 17 up to 16.1 Ma. However, a recent radiometric dating of a volcanic ash layer, located at the base of the Lučane section (Fig. 6) and 96 m below the large mammal bed, points to the earliest Middle Miocene (Olujić, 1999; Jurišić-Polšak and Bulić, 2007). The magnetostratigraphic data by Mandic et al. (2007) confirms this early Middle Miocene age. They discovered a long reversal covering most of the section, which can be correlated with a long reversed period that occurs exactly at the base of the Middle Miocene (Gradstein et al., 2004).

3. Methods

Thirty-nine samples rich in palynomorphs have been studied for pollen analysis from which thirty-six come from sediments from the Lučane section (Fig. 3) and three (MA-77, MA-80 and MA-81) come from lateral subsections to that interval (Fig. 3). Parts of the succession dominated by marly limestones show very bad pollen preservation and are unsuitable for detailed palynological investigation. The 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. Separation of the palynomorphs from the rest of the residue was carried out using $ZnCl_2$ (density = 2). Sieving was performed using a 10 µm nylon sieve. The pollen residue, mounted in glycerine, was prepared on slides. A transmitted light microscope, using ×250 and ×1000 (oil immersion) magnifications, was used for identification and counting of palynomorphs. Because of low representation, spores have not been considered. A minimum of 150 pollen grains (*Pinus* and indeterminable Pinaceae excluded) was counted in each sample analyzed (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 a simplified pollen diagram (Figs. 4 and 5). To highlight basic patterns, thermophilous taxa (including Arecaceae, Rutaceae, *Parthenocissus*, Caesalpiniaceae, Menispermaceae, Cyrillaceae–Clethraceae, *Engelhardia*, *Platycarya*, Taxodiaceae, Sapotaceae, *Symplocos*, Rubiaceae, *Mussaenda*-type and *Microtropis fallax*), xeric plants (Caesalpiniaceae, *Olea*, *Quercus ilex-coccifera* type and grasses) and *Pinus* and other conifers (including *Pinus* and indeterminable Pinaceae, *Cathaya* and *Cedrus*) were grouped together and plotted in Fig. 6. Pollen zonation of the detailed pollen diagram has been made taking into account the variations in relative percentage of the main taxa occurring in the studied section (see explanation below; Fig. 4).

4. Results and discussion

4.1. Pollen stratigraphy of the Lučane section

Based upon the zonation of the pollen data (Fig. 4) we determined five pollen zones. Subzones were differentiated within zones Luč-2 and Luč-4 due to the presence of smaller-scale variability. These data provide a general framework for discussion of vegetation and climate change in the Sinj Basin, SE Croatia, during the early Middle Miocene.

Zones Luč-1 (from ca. 97–87 m in the Lučane section), Luč-3 (from ca. 67–55 m) and Luč-5 (from ca. 13–6 m) and subzones Luč-2-b and Luč-4-b are characterized by the high abundance of thermophilous pollen types, including *Engelhardia* (generally 15–25%), *Platycarya* (to ca. 8%), Sapotaceae (5–10%), *Symplocos* (2–5%), and *Mussaenda*-type (to ca. 5%). *Olea*, a typical Mediterranean xerophilous plant, is also abundant with percentages higher than 5%. Poaceae are generally higher than 5% and so are other grasses.

Subzones Luč-2-a (from ca. 87–77 m in the Lučane section), Luč-2-c (from ca. 75–67 m), Luč-4-a (from ca. 55–2 m) and Luč-4-c (from ca. 20–13 m) are characterized by the high abundance of *Pinus* and indeterminable Pinaceae (generally higher than 45%). *Cathaya* also generally shows percentages above 5% during these time intervals.

4.2. Flora and vegetation

A very rich and diverse flora has been recorded in this study (Figs. 4 and 5). The vegetation has been compared with the one growing today in subtropical to temperate southeastern China (Wang, 1961), the

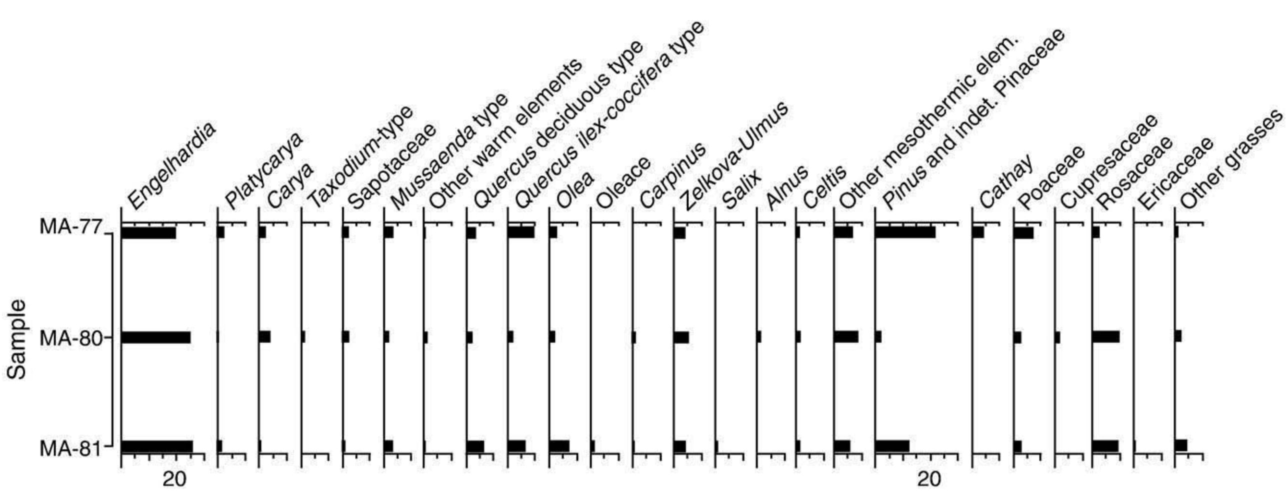

Fig. 5. Simplified pollen diagram of samples taken from the surroundings of the Lučane section. Note that they are not stratigraphically related but they belong to the same "Younger coal-bearing beds" unit. The geographical coordinates for the samples are the following: MA-77: N43 43 04.0 E16 35 18.3; MA-80: N43 43 00.1 E16 35 36.6 and MA-81: N43 43 18.9 E16 35 19.8.

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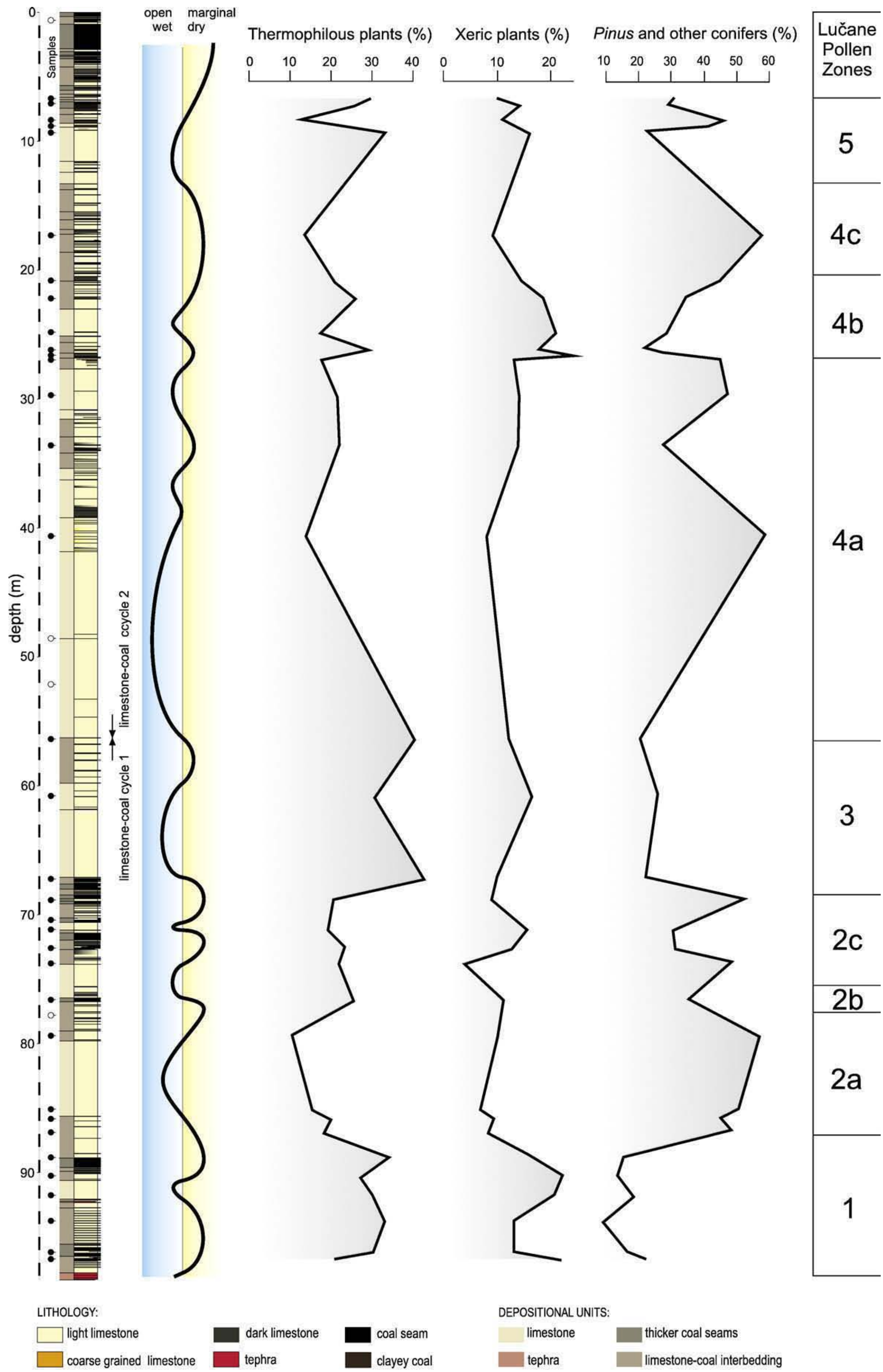
depth (m)
Samples
open wet
marginal dry
Thermophilous plants (%)
Xeric plants (%)
Pinus and other conifers (%)
Lučane Pollen Zones
5
4c
4b
4a
3
2c
2b
2a
1
limestone-coal cycle 1
limestone-coal ccycle 2
LITHOLOGY:
light limestone
coarse grained limestone
dark limestone
tephra
coal seam
clayey coal
DEPOSITIONAL UNITS:
limestone
tephra
thicker coal seams
limestone-coal interbedding

most reliable present-day model (Suc, 1984; Axelrod et al., 1996; Jiménez-Moreno, 2005, 2006; Jiménez-Moreno et al., 2005, 2007a,b). The following plant ecosystems can be distinguished in the pollen data:

1) a swamp (mainly *Taxodium*-type) and riparian environment with *Salix, Alnus*, *Carya*, *Carpinus*, *Zelkova*-*Ulmus* and *Liquidambar*;
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*, Hamamelidaceae, *Engelhardia* and *Hedera*;
3) an evergreen and deciduous mixed forest above 700 m in altitude (Wang, 1961), characterized by deciduous *Quercus*, *Engelhardia*, *Platycarya*, *Carya*, *Pterocarya*, *Fagus*, *Liquidambar*, *Carpinus*, *Celtis* and *Acer*. The shrub level was dominated by Ericaceae and *Ilex*;
4) lastly, from 1000 m up (Wang, 1961), a mid-altitude 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, 1916a; Brusina, 1906, 1907; Buzek, 1982, Žagar-Sakač and Sakač, 1987; Šušnjara and Sakač, 1988; Krizmanić, 1995; Pavelić et al. 2001; Meller and Bergen, 2003; Jurišić-Polšak et al., 1993) show a flora dominated by swampy (mainly *Taxodium*-type), riparian, thermophilous and mesothermic plants indicative of vegetation qualitatively very similar to the one found in this study. The main differences between the flora described in this study and the previous works from Croatia and from Central and Western Europe (synthesis in Jiménez-Moreno, 2005) is the high abundance of *Engelhardia* (sometimes higher than 30%) and the low presence of *Taxodium*-type (always lower than 2%) and *Quercus* deciduous type (mostly lower than 5%) in our pollen spectra. This indicates a very low representation of the swamp vegetation (*Taxodium*) and one of the main components of the deciduous temperate forest (*Quercus* deciduous) and in contrast, a very high presence of *Engelhardia*, a semi-evergreen subtropical species typical from the broad-leaved evergreen forest, in this area.

4.3. Palaeoclimate implications

The general high amount of thermophilous plants growing around the Sinj Basin during the early Middle Miocene suggests a warm, subtropical climate. The climate was also generally quite humid, which was necessary to support the development of such a large association of thermic and hygrophylous 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) or Caesalpiniaceae could either indicate certain seasonality in the precipitation or a xerophilous, azonal vegetation type (Utescher et al., 2007). The warm floral assemblages from the lower Middle Miocene deposits in the Lučane section reflect the Miocene Climatic Optimum (Zachos et al., 2001; Shevenell et al., 2004). These results are in accordance with other palaeobotanical data from Central and Southeastern Europe that also indicate very warm 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: Krizmanić, 1995; Jurišić-Polšak et al., 1993; Serbia: Utescher et al., 2007).

Possibly, the reason why the flora investigated in this study is warmer than the floras from Central and Western Europe is due to the southern palaeogeographic situation of the Balkan Peninsula 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 this area and northern European latitudes, like the one also identified in pollen records from Western Europe (from southern Spain to Switzerland; Jiménez-Moreno and Suc, 2007).

4.4. Climate variability

Pollen results from the Lučane section show the alternation between periods characterized by vegetation rich in thermophilous and xeric plants and other characterized by the abundance of conifers (Fig. 4). Because vegetation is primarily sensitive to temperature and length of the growing season, movements upslope or downslope 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) in lacustrine or marine records, can be good proxies for temperature change. This relationship has been used 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; Popescu et al., 2006; Jiménez-Moreno et al., 2005, 2006, 2007b; Kloosterboer-van Hoeve et al., 2006). Eustatic fluctuations in the lake could be another important factor to take into account in order to understand percentage variations of bisaccate pollen grains (conifers) in our pollen spectra. However, lake level variations have also been interpreted as mostly controlled by climate change (Mandic et al., 2008). Therefore, this bias in the pollen sedimentation would just produce an amplification of the climatic signal (Jiménez-Moreno et al., 2007c) in our pollen record.

Even though the poor resolution of the pollen study in some parts of the section limits the interpretations, our analysis shows that large fluctuations occur in the pollen spectra (see pollen zonation above; Fig. 4), as well as in the sedimentation in the Lučane record (Fig. 6). Mandic et al. (2008) interpreted significant variations in sedimentology from the Lučane section as climatically driven fluctuations in precipitation producing changes in the environment and lake level variations. In order to simplify the comparisons, we combined the thermophilous taxa, xeric plants and *Pinus* and other conifers to compare with the sedimentological data (Fig. 6). Many of the sedimentological variations are synchronous with changes in these pollen taxa, which most likely represent changes in broad-leaved evergreen and deciduous mixed forest and a mid-altitude coniferous forest (Figs. 4 and 6). Increases in thermophilous and xeric pollen (pollen zones Luč-1, Luč-3, Luč-5 and subzones Luč-2-b and Luč-4-b), likely indicating a warming-induced upslope displacement of broad-leaved evergreen forest (as discussed above) are generally associated with the frequent deposition of coal in the basin (Fig. 6), denoting periods of low lake levels and geological evidence of peat-forming paludal swampy conditions. This relationship is especially clear during pollen zones Luč-1, Luč-2-b, the beginning of Luč-3 and Luč-5. Peaks in xeric plants during warm-inferred pollen zones could reflect an increase of the aridity and the drying of certain areas of the lake, supporting our interpretations. Conversely, decreases in thermophilous pollen and increases in pollen originating from the higher elevation conifer forest (pollen subzones Luč-2-a, Luč-2-c, Luč-4-a and Luč-4-c; Figs. 4 and 6) likely indicate a downslope displacement of this vegetation belt. These periods are generally associated with the deposition of deep littoral

Fig. 6. Comparison of the lithology and pollen records from the Lučane section (early Middle Miocene, Sinj Basin, Croatia). From left to right, lithologic log and palaeoenvironmental setting (from Mandic et al., 2008), percentage of thermophilous plants, percentage of xeric plants (including Caesalpiniaceae, *Olea*, *Quercus ilex-coccifera* type and grasses), percentage of *Pinus* and other conifers and pollen zonation identified in this study (see text for more explanation). Note the general coincidence between high-frequency deposition of coal with high percentages of thermophilous and xeric indicators. The position of the pollen samples is indicated by dots. White dots indicate barren pollen samples.

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organic-poor limestones (Fig. 6). We interpret this as denoting periods of high lake levels during cold periods. Even though generally good correspondence exists between the pollen and the sedimentology from the Lučane section, some discrepancies are apparent. For example, a poor correlation exists between the pollen and sedimentological records around ca. 18 m, when pollen data suggest cooler temperatures while the sedimentological data show the deposition of several coal layers, indicating instead a shallowing of the lake (Fig. 6). In general, we can ascribe these discrepancies to several factors, including (a) biases in the pollen sedimentation; (b) lack of a higher-resolution pollen sampling for some parts of the record; (c) presence of smaller-scale climatic and sedimentological variability within long-term climatic cycles denoted by the alternation coal-clay within the coal units; or (d) the sedimentation could also be controlled by tectonics.

The cyclicity on the vegetation and in the sedimentation in the Sinj Basin was probably related to orbital variations in summer insolation, controlling cold–warm cycles and effective precipitation, which in turn influenced lake levels and vegetation in the Sinj Basin. 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), the deposition of Miocene and Pliocene 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) occurred principally when warm and dry climatic phases favouring the development of paludal and swampy conditions and, on the other hand, the deposition of the organic-poor clays or marls happened during colder and moist periods, during higher water levels.

5. Conclusions

Pollen analysis has been carried out in sediments from the lower Middle Miocene from the ancient Lake Sinj Basin (Dinaride Lake System, SE Croatia) in an effort to understand the vegetation, climate and the origin of a previously observed cyclicity limestone–coal.

The abundance of thermophilous and hygrophilous indicators in the pollen spectra indicates that the climate was subtropical and generally humid. The pollen record presented here documents variations in thermophilous and xeric indicators and *Pinus* and other conifers, suggesting movements of the vegetation belts caused by climate change. These fluctuations generally co-vary with sedimentary changes, denoting changes in lake level that could be related to similar climatic forcing factors. Periods of frequent deposition of coal probably happened during warmer and drier climate and, on the contrary, the deposition of organic-poor limestones occurred during colder and moister climate. We suggest that this cyclicity on the vegetation and the sedimentation was probably related to orbital variations in summer insolation, controlling cold–warm cycles and the effective precipitation, which in turn influenced lake levels and vegetation in the Sinj Basin during the early Middle Miocene.

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