

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)

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Abstract

The palynological analysis in the Karpatian–Sarmatian (late Early–Middle Miocene) interval of the cores Tengelic-2 and Hidas-53 (Hungary) reveals the existence of a forest organized in altitudinal belts, developed in a subtropical–warm temperate humid climate, reflecting the so-called Miocene climatic optimum. Pollen changes from the late early Miocene to the late middle Miocene have been observed and are related to climatic changes. The vegetation during the Burdigalian and the Langhian was dominated by thermophilous elements such as evergreen trees and *Engelhardia*, typical of a present day rain and evergreen forest at low altitudes (i.e. SE China). During the Serravallian several thermophilous elements strongly decreased, and some of them disappeared from the central European area. Thus, the rain and evergreen–deciduous mixed forest suffered a great transformation due to the loss and decrease in the abundance of several evergreen plants. This kind of vegetation was progressively substituted by deciduous and mesothermic plants such as deciduous *Quercus*, and *Fagus*, *Alnus*, *Acer*, *Carpinus*, *Ulmus*, *Zelkova*, etc. At the same time, the presence of altitude coniferous trees increased.

This climatic cooling is correlated with global and regional climatic changes.

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1. Introduction

Pollen analyses with a botanical background dealing with Miocene sediments from the Paratethys are rare. Some studies focused on Miocene palynology in the Central Paratethys (Planderová, 1990; Nagy, 1991, 1992, 1999) but methodological aspects, such as pollen taxonomy and the lack of any quantitative information, are questionable.

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In this study, pollen grains are not used for biostratigraphic purposes, as an independent biostratigraphic datation was available (see below), but for botanical and climatic information. Extensive pollen countings and a statistical treatment of the data were done in order to obtain high-quality information about floral diversity, composition of the vegetation and to better visualize vegetation and climatic changes.

The aim of this article is to reconstruct and interpret the developed vegetation around the Pannonian Basin (Hungary) during the late Early and Middle Miocene. This is based on an already published high-resolution pollen analysis of the core Tengelic-2 (Jiménez-Moreno et al., 2005) and new data of the Hidas-53 core using botanical taxonomy and a quantitative approach of the pollen data. Palynological information allows for paleoenvironmental reconstructions in order to determine the influence of climatic changes in the origin and evolution of the studied vegetation.

2. Regional setting

The rise of the Alpine mountain belt led to a partition of the Tethyan Ocean at about the Eocene/Oligocene boundary. This geodynamic process caused the Tethys to disappear as a paleogeographic and paleobiogeographic entity and two distinct paleogeographic areas evolved during the Neogene — the Mediterranean and the Paratethys seas. This geographic separation also resulted in a biogeographic differentiation and has necessitated the establishment of separate chronostratigraphic/geochronologic scales. Within the Paratethys, a distinction between western, central and eastern Paratethys reflects internal differentiation and a complex pattern of changing seaways and landbridges between the Paratethys and the Mediterranean as well as with the western Indo-Pacific (e.g., Rögl, 1998).

Within the Paratethys realm, one basin — the Pannonian Basin — has served as the focus of our studies (Fig. 1). This basin is of back-arc type and formed during the Middle Miocene. It is encircled by the Alps to the west, the Carpathians to the north and east and the Dinarides to the south (Royden and Horváth, 1988; Meulenkamp and Sissingh, 2003) (Fig. 1, 2). The Pannonian basin includes several sub-basins, some of which are filled with more than 5500 m of Neogene sediments (Kovac et al., 2004).

As with other basins of Paratethys during the Neogene, the Pannonian basin experienced a long-term trend of decreasing marine influence and concomitant reduction in the size of their marine depositional domains (Rögl, 1998; Meulenkamp and Sissingh, 2003). Never-

theless, during the Early and Middle Miocene, broad connections existed with the Mediterranean Sea that enabled a free faunal exchange between those two regions (Harzhauser et al., 2003; Fig. 1). Consequently, marine organisms are similar in both the Mediterranean Basin and Pannonian Basin at this time. The first impairment of marine connections is evident in the Late Badenian (Early Serravallian) when dysaerobic bottom conditions and a stratified water column characterized the Paratethyan realm (Kovac et al., 2004). With the onset of the Sarmatian, marine connections to the Mediterranean almost completely ceased, this being reflected by the development of a highly endemic molluscan fauna (Harzhauser and Piller, 2004). Finally, at the Sarmatian/Pannonian boundary (Serravallian/Tortonian boundary), the central Paratethys became entirely restricted and the brackish Lake Pannon established.

3. Materials and methods

3.1. Cores Tengelic-2 and Hidas-53

The cores Hidas-53 and Tengelic-2 are located in the Pannonian Basin in southern Hungary (46° 15'58" N, 18° 29' 37" E and 46° 31' 59.9" N, 18° 43' E respectively; Fig. 2), close to the Mecsek Mountains and between the cities of Paks and Pécs. They are separated by ca. 10 km.

Marine sediments of Badenian and Sarmatian age (collectively Langhian and Serravallian) are present in both cores (Fig. 3). Age control is mainly based on calcareous nannofossils, mollusks, planktonic foraminifera and lithostratigraphy (Földi, 1966; Korecz-Laky, 1968, 1982; Bohn-Havas, 1982; Nagymarosi, 1982; Hámor, 1995).

The Karpatian is characterized mainly by terrigenous effusive volcanites, known as the Tar Dacite-Tuff Formation which are more abundant in the Tengelic-2 core than in Hidas-53 (Fig. 3), and clays from the Tekeres Schlier Formation. The volcanic sediments have been dated in the Tengelic 2 core by K/Ar radiometry, with the youngest sample (at 872 m core depth) yielding an age of 16 ± 0.7 Ma (Halmai et al., 1982). Intercalations of layers of lacustrine to brackish sediment in the Tengelic-2 core reflect the progressive transition from continental to brackish conditions.

The Karpatian is discordantly overlain by the Badenian Clay Formation starting with layers of terrestrial coarse deposits. The following grey siltstones, dark argillaceous marls and grey sandstones are dated as late Early Badenian, and assigned to the Upper Lagenidae Zone based on a predominance of genera

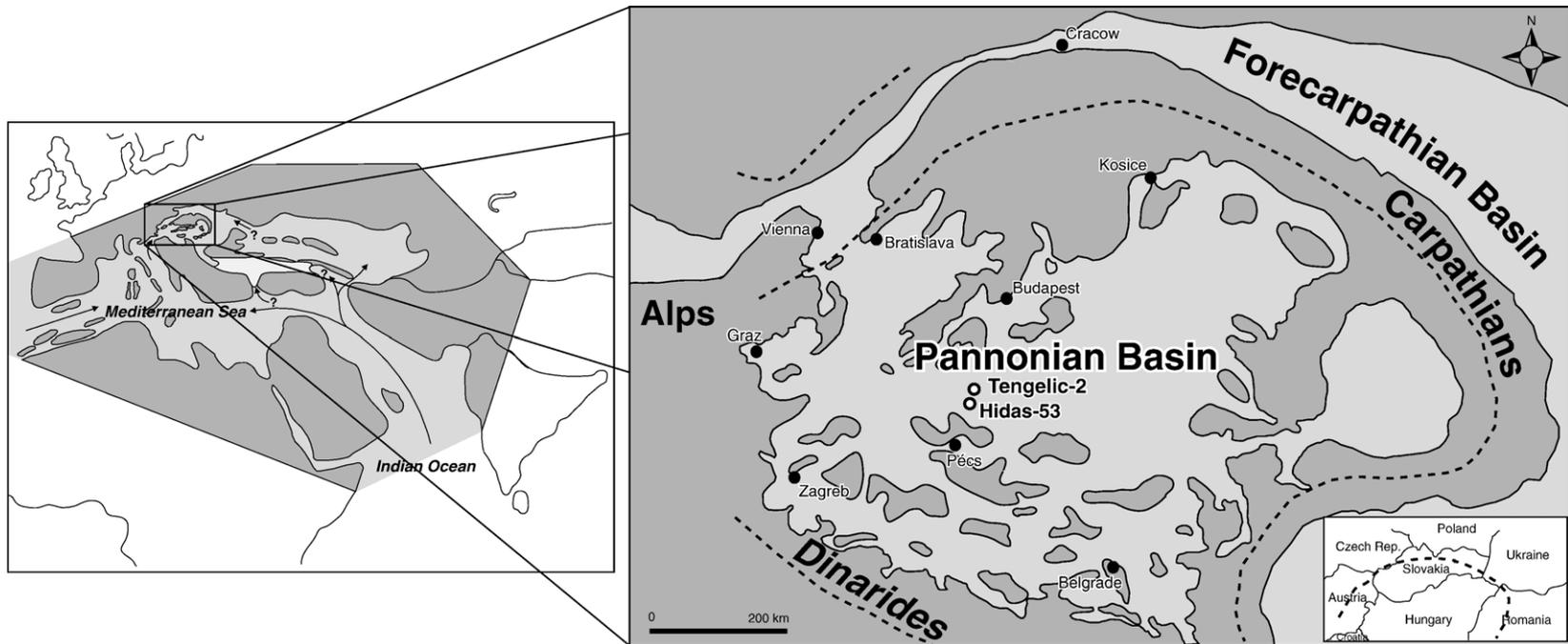


Fig. 1. Palaeogeographic map of the Pannonian Basin during the Badenian (Middle Miocene) after Hámor (1995) and Röggl (1998). The location of the Tengelic-2 and Hidas-53 boreholes is indicated by white dots. The dashed line indicates axes of the main structural highs. Light grey shading indicates marine conditions.

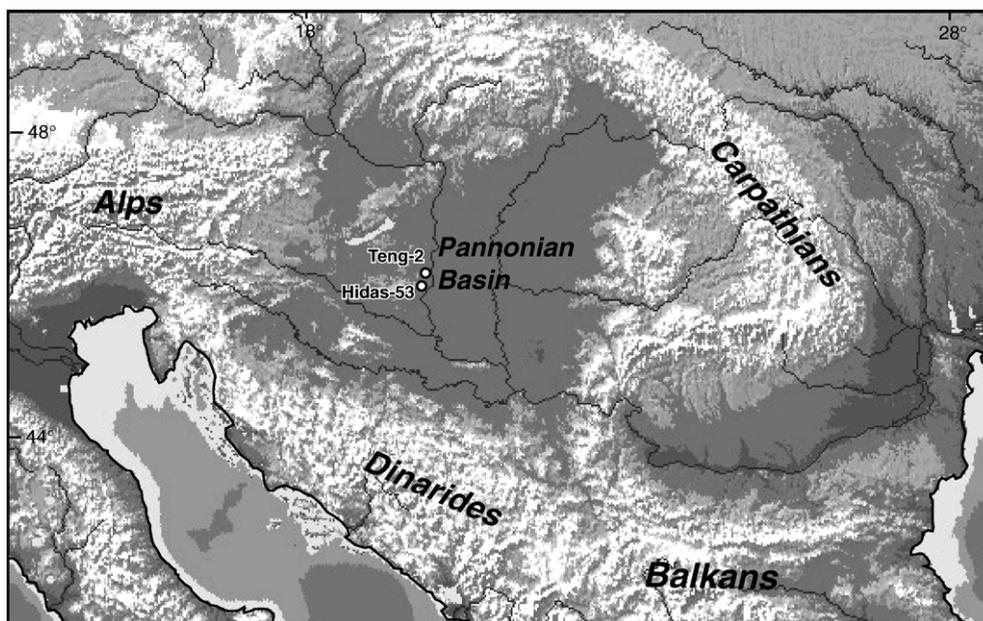
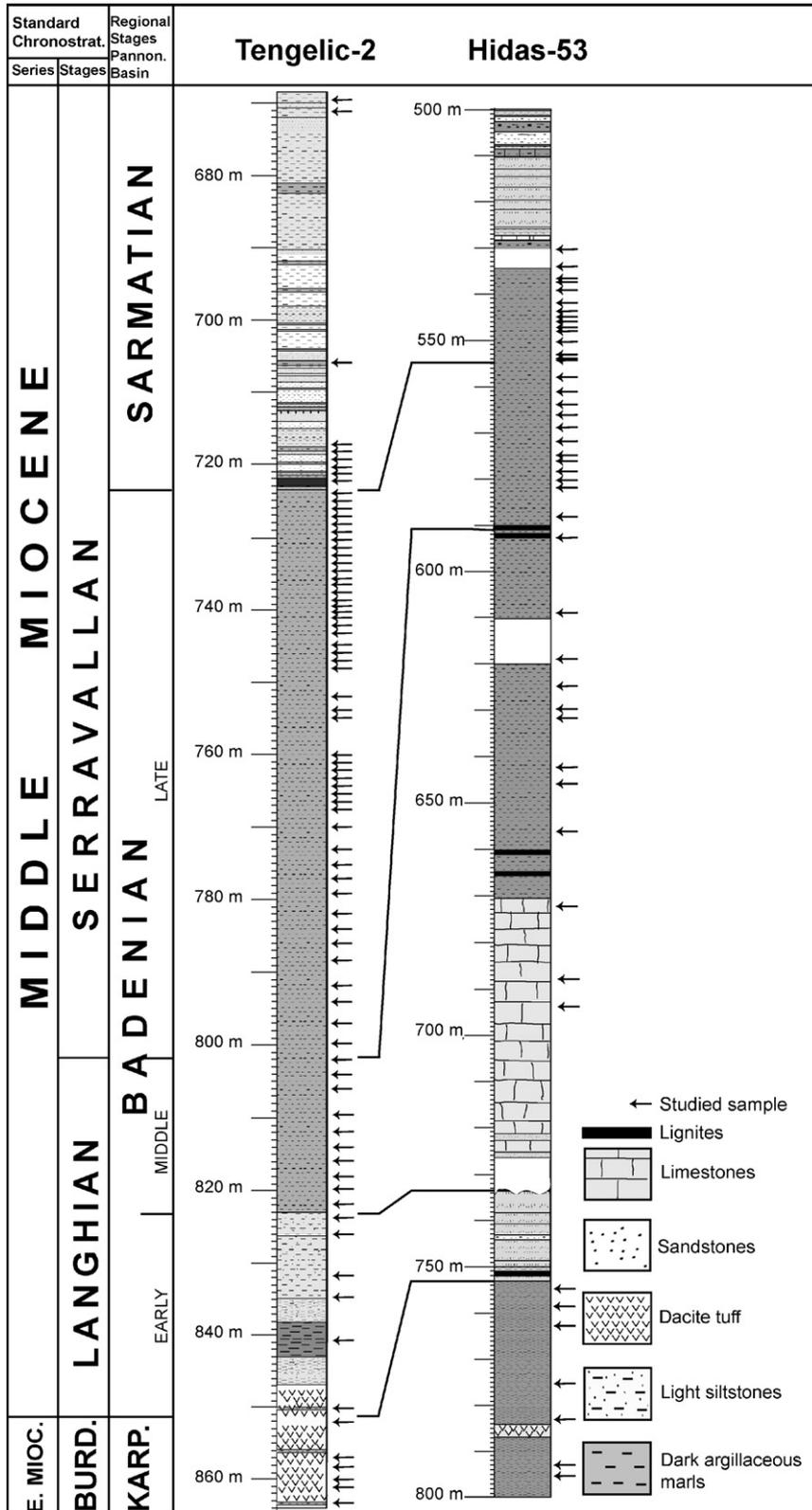


Fig. 2. Geographic position of the Hidas-53 and Tengelic-2 boreholes within the Pannonian basin. The main reliefs of this region are also indicated.

and species of the family Lagenidae (according to the biozonation of Grill, 1941, 1943) co-occurring with *Orbulina universa* and *Orbulina bilobata* (Korecz-Laky, 1968, 1982). Following Rögl et al. (2002), this typical Paratethyan assemblage can be correlated with the planktonic foraminiferal zone M6 of Berggren et al. (1995). Therefore, marine deposits of the lower Lagenidae Zone, representing the Early Badenian and comprising equivalents of the planktonic foraminiferal zone M5b of Berggren et al. (1995) and the nannoplankton zone NN4 of Martini and Worsley (1970) are missing. Indeed, calcareous nannofossils for this interval are dominated by *Reticulofenestra minuta*, *R. pseudumbilica*, *Coccolithus pelagicus*, *Cyclococcolithina rotula*, *C. jafari*, *Helicopontosphaera kamptneri*, *Rhabdosphaera pannonia*, *Sphenolithus heteromorphus*, *Discoaster exilis*, *D. dilatus*, and *D. formosus*, and allow assignment to Zone NN5 of Martini and Worsley (1970) (Nagymarosi, 1982). At that time, the area was already occupied by the shallow Paratethys Sea. This part of both cores can therefore be correlated with the upper Langhian of the Mediterranean standard scale.

A lithological change coincident with a biostratigraphic one, at 823.4 m in the Tengelic-2 core and at 733.0 m in the Hidas-53 core, suggests a brief hiatus, and marks the onset of middle and upper Badenian sedimentation as represented by the Hidas Lignite Formation (only represented in the Hidas-53 core) and Szilágy Formation. Lacustrine limestones and lignites characterise the first part of this local stage in the Hidas-53 core (Hidas Lignite Fm.). The homogeneous, dark, organic-rich argillaceous marls yield abundant molluscs such as *Turritella* and *Corbulacharacterize* the upper part and the whole middle and late Badenian in the Tengelic-2 core. The benthic foraminiferal assemblage, with frequent *Spirorutilus carinata*, *Pavonitia styriaca*, *Uvigerina venusta* (Korecz-Laky, 1968, 1982), allows assignment to the middle Badenian *Spirorutilus* Zone based on cross-correlation with the nannofossil data and, above this, to the upper Badenian *Bolivina–Bulimina* Zone, based on the regional eco-zonation of Grill (1941, 1943). It should be noted that assignment to the *Bulimina–Bolivina* Zone is considered most likely, although such index fossils as *Velapertina* and *Pappina*

Fig. 3. Geological log of the Karpatian–Sarmatian sediments of the cores Tengelic-2 and Hidas-53 (Hungary) with their chronostratigraphic framework, showing the position of samples analysed in the present study. The age assignment is based on planktonic foraminifera, nannofossils and molluscs (Földi, 1966; Bohn-Havas, 1982; Korecz-Laky, 1968; 1982; Nagymarosi, 1982). Stratigraphic relationships and chronostratigraphy are based on Gradstein et al. (2004) and Steininger et al. (1990, 1996).



neudorfensis are missing. The calcareous nannofossil flora indicates Zone NN5 up to 802 m in the Tengelic-2 core (Nagyvarosi, 1982), allowing a correlation with the uppermost Langhian and lowermost Serravalian. The upper part of the Szilágy Formation, from 802 to 723 m in the Tengelic-2 core, was dated as NN6 (Nagyvarosi, 1982) based on the absence of *Sphenolithus heteromorphus*, pointing to a Serravallian age (Fornaciari et al., 1996).

According to Kóky (1996), the uppermost part of the Badenian in the Tengelic-2 core was eroded during an important regression that represents a type 1 third-order sequence boundary. The Sarmatian therefore lies on an unconformity at 723 m. It comprises sands, limestones, light-grey clays and lignites of an unnamed formation reflecting more shallow marine and freshwater-paludal conditions that developed in the now isolated inland sea with aberrant water chemistry (Hámor, 1995; Rögl, 1998; Harzhauser and Piller, 2004).

Within the Central Paratethys, the Badenian–Sarmatian boundary is characterized by an important biotic change. The foraminiferal fauna becomes characterized by a small number of species but a large number of individuals dominated by the genera *Elphidium*, *Porosonion* and *Rotalia* (Rögl, 1998). Changes in the calcareous nannofossil flora resulted from a shift in water chemistry rendering a direct comparison with Mediterranean zonations difficult. Several dinocysts vanished at that time such as *Cordosphaeridium minimum* sensu Benedek and Sarjeant (1981), *Reticulosphaera actinocoronata*, the organic linings of calcareous cysts, *Labyrinthidium truncatum*, and *Cerebrocysta poulsenii*. Cosmopolitan neritic species (e.g. *Spiniferites* spp., *Cleistosphaeridium placacanthum*, *Operculodinium* spp.) and extant euryhaline species (*Lingulodinium machaerophorum*) dominate in the Sarmatian (Jiménez-Moreno, 2005). *Impagidinium* spp. and *Nematosphaeropsis labyrinthus* are no longer present, indicating the disappearance of open-marine influence by this time (Jiménez-Moreno, 2005). Moreover, in both cores the nannoplankton, the foraminiferal and the dinocyst diversity drops considerably with the onset of the Sarmatian (Nagyvarosi, 1982; Korecz-Laky, 1968, 1982; Jiménez-Moreno, 2005). The Sarmatian nannofossil floras comprise long-ranging euryhaline species including *Reticulofenestra pseudoumbilica*, *Coronosphaera mediterranea*, *Braarudosphaera bigelowi* and *Cyclococcolithus macintyreii*. Aside from the endemic foraminiferal assemblage and endemic mollusc species such as *Venerupis tricuspis* and *Chartocardium carasi* (syn. *C. gleichenbergense*), the abundance of *Cyclococcolithus macintyreii* in these sediments locally (within the

Paratethys area) indicates a Sarmatian age (Nagyvarosi, 1982).

3.2. Sample collection and chemical processing

A total of 124 samples, comprised of 78 from Tengelic-2 and 46 from the Hidas-53 cores, have been analyzed (Fig. 3). Dinocysts have also been studied (Jiménez-Moreno, 2005; Jiménez-Moreno et al., 2005), and in most samples are less abundant than the pollen grains. From samples initially weighing about 50 g each, 20–30 g were processed for palynological analysis. This involved treatment using cold HCl (35%) and HF (70%) to remove carbonates and silica, and separation of the organic residue by means of ZnCl (density >2.0). No oxidizing reagents or alkalis were used, as these can be harmful to some pollen grains and dinocysts. The residue was sieved at 10 µm using a nylon mesh, mixed with glycerine, and mounted on microscope slides. Slides were counted using a Zeiss Ultraphot II transmitted light microscope at ×250, ×630 and ×1000 (oil immersion) magnifications. At least 150 pollen grains, *Pinus* and indeterminate Pinaceae excluded, were enumerated for each analysed sample.

3.3. Taxonomical determination and statistical treatment

In this study, a botanical identification of the pollen grains was carried out. Classification was then performed comparing the fossil pollen grains with their living relatives from several pollen atlases, the photograph collection stored in the laboratory of Lyon, and also using the Photopal website (<http://medias.obs-mip.fr/photopal>).

Based on the results of the pollen spectra, detailed pollen diagrams and standard synthetic pollen diagrams (Suc, 1984) without *Pinus* and Pinaceae have been constructed. In these later diagrams, pollen taxa have been grouped into 10 different groups of taxa based on ecological criteria (Nix, 1982) in order to clearly visualise the composition and structure of the vegetation (see Table 1) and compare the climatic signal with isotopic and other geochemical data. This method has been proven as a very efficient tool for high-resolution climatic studies characterising warm–cold alternations related to Milankovitch cycles either for the Tengelic-2 core (Miocene) (Jiménez-Moreno et al., 2005) and the Pliocene (Popescu, 2001; Popescu et al., in press).

In this paper, only the detailed pollen diagram of the Hidas-53 core is shown (Fig. 4) as the one from the Tengelic-2 core has already been published by Jiménez-Moreno et al. (2005).

Table 1

List of the taxa identified in cores Hidas-53 and Tengelic-2 grouped by ecological requirements in order to plot the synthetic diagrams

Megathermic elements	Araliaceae	<i>Tamarix</i>	<i>Liquidambar</i>	<i>Artemisia</i>
Rutaceae	Taxodiaceae	Fabaceae–Papilion.	<i>Hamamelis</i>	<i>Ephedra</i>
Solanaceae	<i>Taxodium</i> type	<i>Buxus sempervirens</i>	<i>Tilia</i>	Caryophyllaceae
<i>Alchornea</i>	Cyrillaceae–Clethrac.	<i>Restio</i>	<i>Acer</i>	Ericaceae
Euphorbiaceae	Theaceae	<i>Celtis</i>	Moraceae	Urticaceae
<i>Mussaenda</i> type	<i>Distylium</i>	<i>Zelkova</i>	Resedaceae	<i>Malvaceae</i>
			Meso-microthermic elements	
Rubiaceae	<i>Disanthus</i>	<i>Ulmus</i>		Cyperaceae
Melastomataceae	<i>Rhodoleia</i>	<i>Cissus</i>	<i>Cedrus</i>	<i>Potamogeton</i>
Acanthaceae	cf. <i>Corylopsis</i>	<i>Vitis</i>	<i>Sciadopitys</i>	Liliaceae
Meliaceae	Hamamelidaceae	<i>Leea</i>	<i>Tsuga</i>	Apiaceae
<i>Eustigma</i>	Menispermaceae	<i>Ilex</i>	Microthermic elements	Geraniaceae
Simarubaceae	Agavaceae	Oleaceae	<i>Abies</i>	Polygonaceae
<i>Buxus bahamensis</i> type	Chloranthaceae	<i>Ligustrum</i>	<i>Picea</i>	Ericaceae
Mega-mesothermic elements	<i>Ricinus</i>	<i>Fraxinus</i>	Non-significant elem.	Resedaceae
<i>Myrica</i>	Cathaya	Caprifoliaceae	Indet. grains	Plumbaginaceae
<i>Symplocos</i>	Mesothermic elements	<i>Lonicera</i>	Indeterminable grains	Bassicaceae
<i>Symplocos paniculata</i> type	<i>Fagus</i>	<i>Viburnum</i>	Rosaceae	<i>Tricolporopollenites sibiricum</i>
Arecaceae	<i>Quercus</i> –deciduous type	<i>Rhus</i>	Ranunculaceae	<i>Rumex</i>
Sapotaceae	<i>Castanea</i> – <i>Castanopsis</i> type	Anacardiaceae	Cupressaceae	<i>Mercurialis</i>
			Mediterranean xerophytes	
Loranthaceae	<i>Pterocarya</i>	<i>Salix</i>		<i>Thymelaceae</i>
<i>Engelhardia</i>	<i>Carya</i>	<i>Populus</i>	<i>Olea</i>	Nymphaeaceae
<i>Platycarya</i>	<i>Eucommia</i>	Rhamnaceae	<i>Phillyrea</i>	<i>Potamogeton</i>
<i>Parthenocissus</i>	<i>Juglans</i> cf. <i>cathayensis</i>	<i>Sequoia</i> type	<i>Quercus ilex</i> – <i>coccifera</i> type	<i>Sparganium</i> – <i>Typha</i>
Caesalpiniaceae	<i>Juglans</i>	<i>Nyssa</i>	Herbs & shrubs	Boraginaceae
<i>Rhoiptelea</i>	<i>Betula</i>	<i>Hedera</i>	Poaceae	<i>Galium</i>
<i>Cornus</i>	<i>Alnus</i>	<i>Hamamelis</i>	Asteraceae–Asteroidae	<i>Sanguisorba</i>
<i>Microtropis fallax</i>	<i>Carpinus</i>	<i>Parrotia</i>	Asteraceae–Cichoroidae	
Celastraceae	<i>Carpinus orientalis</i>	<i>Fothergilla</i>	Amaranthaceae–	
			Chenopodiaceae	
Myrtaceae	<i>Ostrya</i>	<i>Platanus</i>	<i>Plantago</i>	

Pollen data will be available, after publication, on the web from the “Cenozoic pollen and climatic values” database (CPC) (<http://cpc.mediasfrance.org>).

4. Results

4.1. Pollen analysis

In both cores pollen spectra show the dominance of *Pinus* and indeterminable Pinaceae with values between 88.7% and 4.3% in the Hidas-53 and 81.9% and 4.1% in the Tengelic-2 reflecting the usual over-representation of these vesiculate pollen grains in marine sediments (Jiménez-Moreno et al., 2005, this study). Apart from this, mega-mesothermic trees such as *Taxodium* type and *Engelhardia*, and mesothermic trees, like *Quercus* deciduous type, are the most abundant (Figs. 4 and 5). The mega-mesothermic elements are more copious in the Tengelic-2 core than in the Hidas-53 where mesothermic trees (mainly *Quercus* deciduous type,

Salix, *Zelkova*, *Liquidambar*, *Carya* and *Acer*) dominated (Figs. 4 and 5). *Cathaya*, meso-microthermic trees (*Cedrus* and *Tsuga*) and microthermic trees (*Abies* and *Picea*) are present along both cores. Small amounts of megathermic elements, such as Euphorbiaceae, Rubiaceae, *Mussaenda* type, *Alchornea*, Melastomataceae, *Sindora*, *Eustigma*, *Acacia* and Rutaceae, occur in all the samples (Figs. 4 and 5). The herbs and shrubs, which rarely reach more than 5%, are dominated by Poaceae, Amaranthaceae–Chenopodiaceae, *Plantago*, *Rumex*, *Sparganium*–*Typha* and Ericaceae. Taxa from the non-significant elements group (mainly Rosaceae) are in some cases abundant (i.e., in Hidas-53) (Figs. 4 and 5). Taxa from the rest of the ecological groups (Cupressaceae and Mediterranean xerophytes) are scarce.

During the middle Miocene, early Badenian–Sarmatian for the Tengelic-2 core and late Badenian–Sarmatian for the Hidas-53 core, important changes in the flora are observed as several megathermic and mega-mesothermic

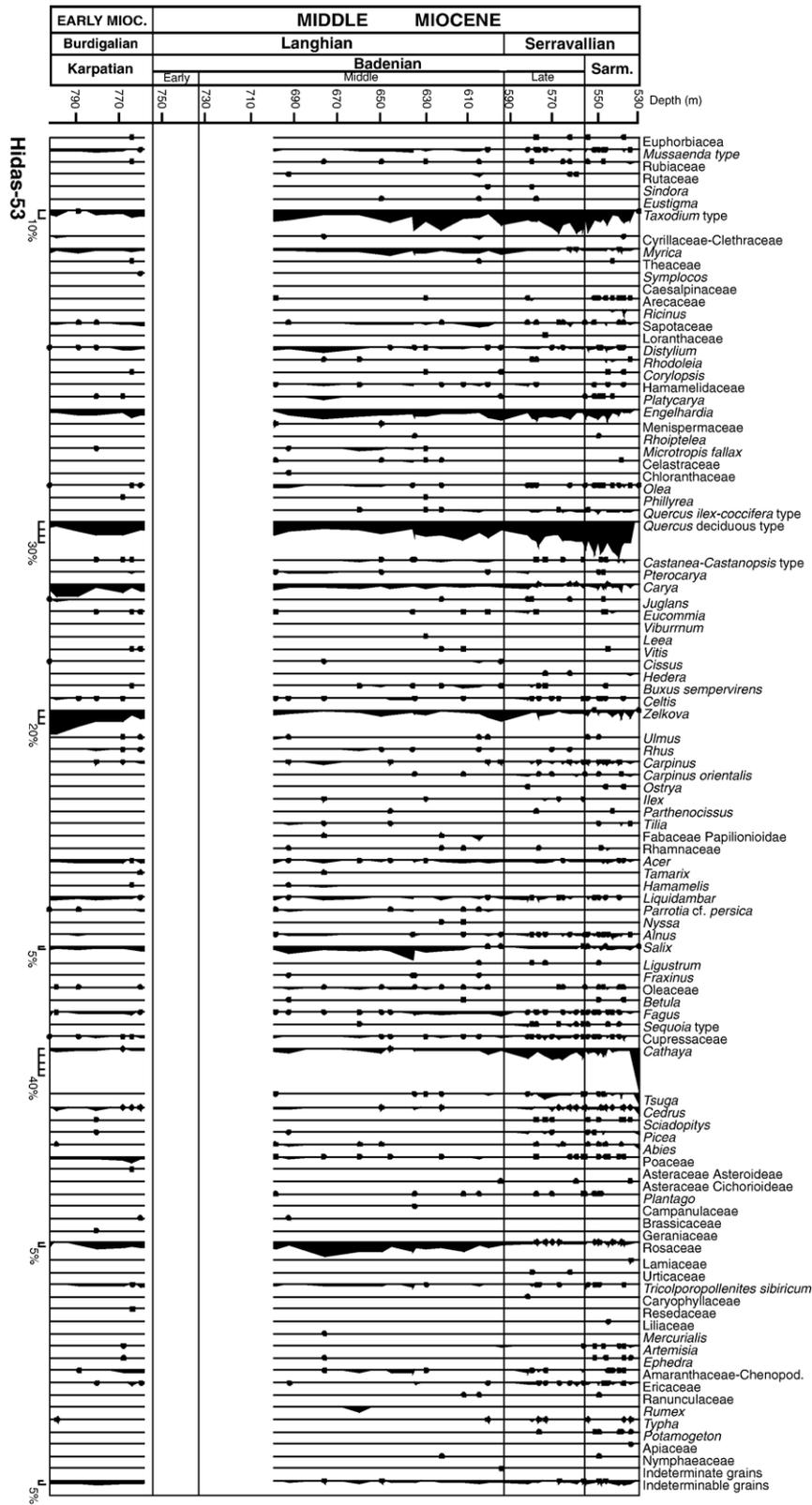


Fig. 4. Detailed pollen diagram of the Hidas-53 core without *Pinus* and indeterminate Pinaceae. A solid dot indicates taxa recorded in the counts but frequencies below 1%.

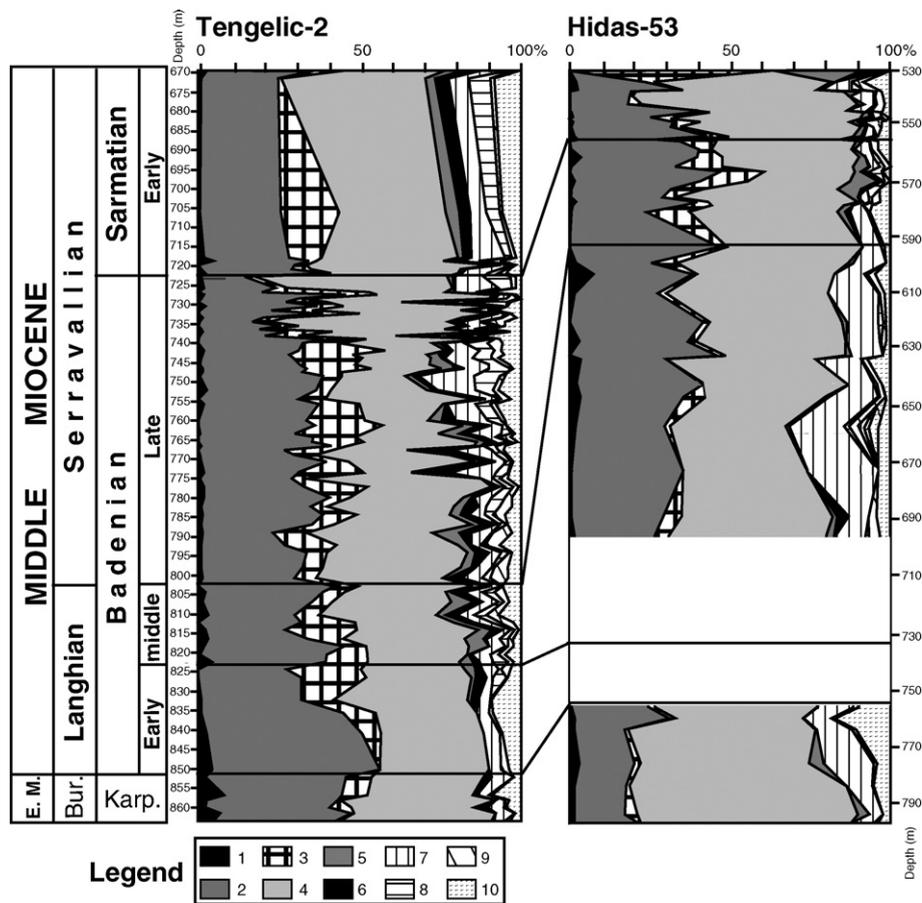


Fig. 5. Pollen synthetic diagram without *Pinus* and indeterminate Pinaceae of the Hidas-53 and Tengelic-2 cores. Grouping was done regarding the ecology of the plants (see text for explanation). Legend numbers are: (1) megathermic elements; (2) mega-mesothermic elements; (3) *Cathaya*; (4) mesothermic elements; (5) meso-microthermic elements (mid-altitude elements); (6) microthermic elements (high-altitude elements); (7) non-significant elements; (8) Cupressaceae; (9) Mediterranean xerophytes; (10) herbs and shrubs.

elements decreased and many of them disappeared from this region letting the mesothermic, meso-microthermic and microthermic elements increase (Figs. 4 and 5).

4.2. Pollen distribution of two selected taxa: *Engelhardia* vs. deciduous *Quercus*

Engelhardia, a present day mega-mesothermic (i.e., subtropical) laurophyllous and mainly evergreen tree from the Juglandaceae family (Pecan and Walnut trees) typical from the low altitude mixed broad-leaved and evergreen forests in subtropical SE China (Wang, 1961) is very abundant in the samples from both Hidas-53 and Tengelic-2 cores (Fig. 6).

Deciduous *Quercus*, on the contrary, today a deciduous-mesothermic tree (i.e., warm-temperate) from the Fagaceae family (Oak trees), typical of deciduous forests in septentrional latitudes, is also very abundant in the

pollen spectra of the Hidas-53 and Tengelic-2 cores (Fig. 6).

Most of the time, the sum of the percentages of these two taxa forms a large part of the total percentage of the pollen spectra without *Pinus* and indeterminate Pinaceae and never reaches a value below 10%. The maximum value is 60.1% and the average value is 30.25% of the total sum of the pollen grains (without *Pinus* and indeterminate Pinaceae) (Fig. 6).

Engelhardia shows a stepwise decrease along the Tengelic-2 and Hidas-53 cores from the Karpatian to the Sarmatian age. This is very clear along the Tengelic-2 core and the late Badenian–Sarmatian part of the Hidas-53 core (Fig. 6). This decreasing trend shows, though, numerous short-term variations, mainly related to orbital climate forcing (see Jiménez-Moreno et al., 2005 for explanation). The over-representation of riparian plants in the lowest part of the Hidas-53 core would made

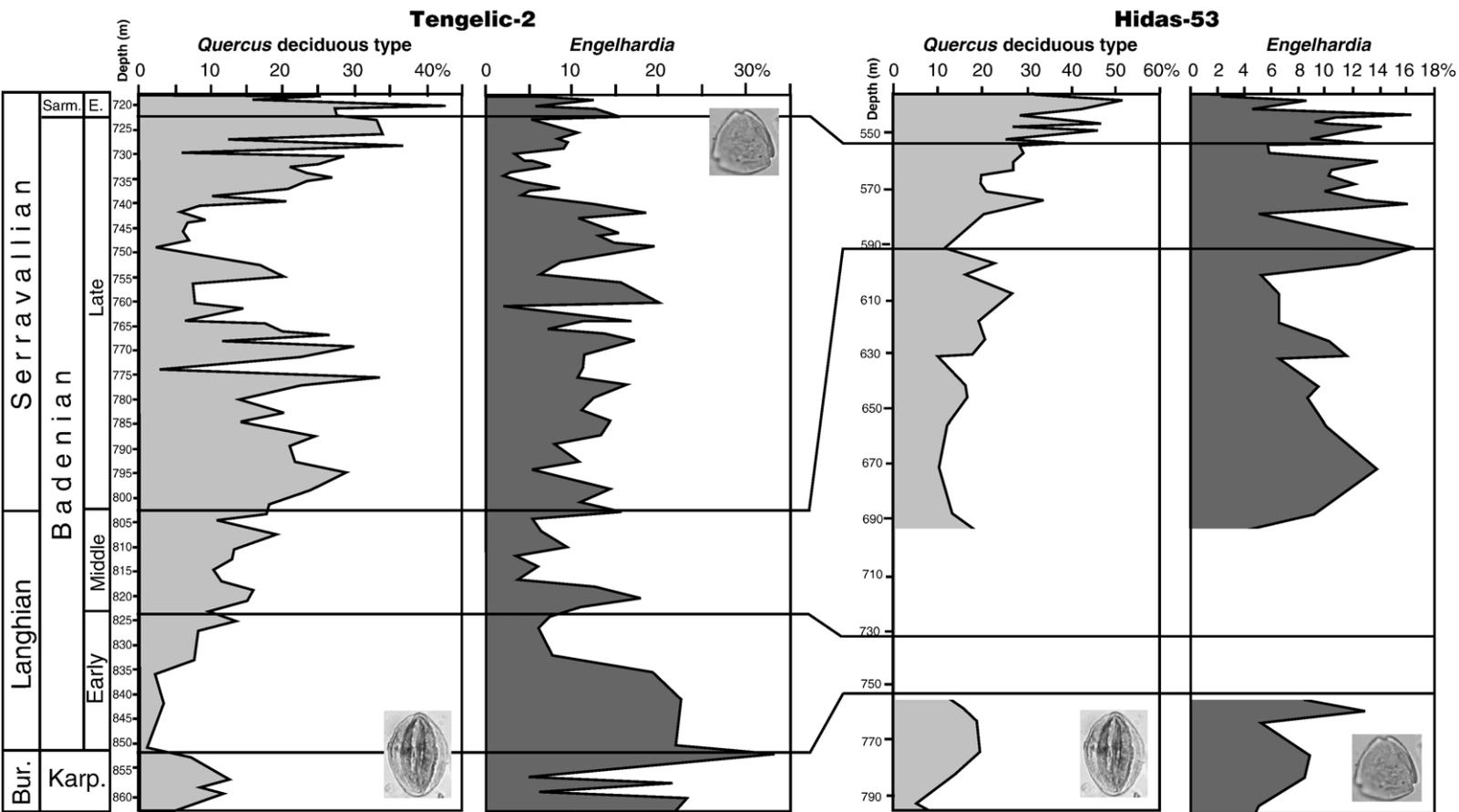


Fig. 6. Evolution of the percentages of deciduous *Quercus* and *Engelhardia* along the Karpatian to Sarmatian part of the Tengelic-2 and Hidas-53 cores. Note that deciduous *Quercus* increases upwards and on the contrary, *Engelhardia* decreases.

percentages of *Engelhardia* be lower than the expected in this core and the observed in the Tengelic-2 core. On the other hand, the deciduous *Quercus* shows a pronounced increase during the same time-span in both cores (Fig. 6).

5. Discussion

5.1. Flora and vegetation

In addition to *Engelhardia* and deciduous *Quercus*, a very rich and diverse flora has been identified for the Miocene and consisted of elements found presently in different geographic areas:

- 1) Subtropical and tropical Africa, America and Asia (*Platycarya*, Taxodiaceae, Hamamelidaceae, *Myrica*, Sapotaceae, etc.);
- 2) Septentrional latitudes (*Acer*, *Alnus*, *Betula*, Cupressaceae, *Fagus*, *Populus*, *Salix*, etc.);
- 3) Mediterranean region (*Olea*, *Phillyrea*, *Quercus illex-coccifera* type, etc.).

All of these taxa grew in the eastern European area during the Miocene.

The vegetation was characterized by a complex mosaic due to its dependency on several factors: water availability, characteristics of the soil, orientation, etc. The most important factor, similar to present day, would be altitude, controlling temperature and precipitations. Therefore, the vegetation was organized in altitudinal belts, which have been compared with the ones found today in subtropical to temperate SE China (Wang, 1961), the most reliable model. The following have been distinguished:

- 1) a coastal marine environment characterized by the presence of halophytes (Amaranthaceae–Chenopodiaceae, *Armeria*, etc.);
- 2) broad-leaved rain forest and evergreen forest, from sea level to around 700m in altitude depicted by *Taxodium* type, *Myrica*, *Rhus*, Theaceae, Cyrillaceae–Clethraceae, Euphorbiaceae, *Distylium*, *Castanea–Castanopsis* type, Sapotaceae, Rutaceae, *Mussaenda* type, *Ilex*, *Hedera*, *Ligustrum*, *Jasminum*, Hamamelidaceae, *Engelhardia*, *Rhoiptelea*, etc.;
- 3) an evergreen and deciduous mixed forest, above 700 m in altitude; characterised by deciduous *Quercus*, *Engelhardia*, *Platycarya*, *Carya*, *Pterocarya*, *Fagus*, *Liquidambar*, *Parrotia*, *Carpinus*, *Celtis*, *Acer*, etc. Within this vegetation belt, a riparian vegetation has been identified, composed of *Salix*, *Alnus*, *Carya*,

- Carpinus*, *Zelkova*, *Ulmus*, etc. The shrub level was dominated by Ericaceae, *Ilex*, Caprifoliaceae, etc.,
- 4) above 1000 m, a middle altitude deciduous and coniferous forest with *Cathaya*, *Cedrus* and *Tsuga*.
 - 5) finally, above 1800 m in altitude a coniferous forest with *Abies* and *Picea*.

5.2. Vegetation dynamics: progressive increase of deciduous trees in the forest

5.2.1. Karpatian–Badenian (late Burdigalian–Langhian)

The regular occurrence and abundance of thermophilous species typical of the lowest altitudinal belts described above is characteristic for the vegetation of that time.

The coastal marine environment was then occupied mainly by several halophytes. Other studies in surrounding areas show that an impoverished *Avicennia*'s mangrove also populated this kind of environment (Nagy and Kókay, 1991; Nagy, 1999; Jiménez-Moreno, 2005).

Higher in altitude, the lowlands were populated by a broad-leaved rain forest and evergreen forest, depicted by *Alchornea*, *Rhus*, Theaceae, Cyrillaceae–Clethraceae, *Buxus bahamensis* type, Rubiaceae, Chloranthaceae, Euphorbiaceae, *Distylium*, *Castanea–Castanopsis*, Sapotaceae, Rutaceae, *Mussaenda* type, *Ilex*, *Hedera*, *Ligustrum*, Hamamelidaceae, *Engelhardia*, *Rhoiptelea*, etc. Within this vegetation belt, the swamp forests were also well developed during this timespan. Its components, such as *Taxodium* type, *Nyssa* and *Myrica*, show comparatively high values in the pollen spectra. The palaeogeographic situation and very humid conditions at that time most likely favoured the wide distribution of swamp forests and ecologically related riparian forests with *Platanus*, *Liquidambar*, *Zelkova*, *Carya*, *Pterocarya* and *Salix*. These azonal elements were very abundant in the Karpatian to middle Badenian of the Hidas-53 core reflecting local very humid conditions.

An evergreen and deciduous mixed forest mainly depicted by mesothermic elements such as deciduous *Quercus*, *Carya*, *Pterocarya*, *Fagus*, Ericaceae, *Ilex*, Caprifoliaceae, *Liquidambar*, *Parrotia*, *Carpinus*, *Celtis*, *Acer*, etc., characterised areas of higher altitude. Within this belt, a riparian vegetation has been identified, composed of *Salix*, *Alnus*, *Carya*, *Carpinus*, *Zelkova*, *Ulmus*, etc.

It should also be mentioned that conifer pollen, mainly *Pinus* and indeterminate Pinaceae, can be particularly abundant, presumably because of the capacity of bisaccate pollen for long distance transport (Turon, 1984; Heusser, 1988; Suc and Drivaliari, 1991;

Cambon et al., 1997; Beaudouin, 2003). During the Badenian the basin developed its largest extension so that the cores have the maximum distance from the coastline (Fig. 3).

Middle and high altitude elements (*Tsuga*, *Cedrus*, *Abies* and *Picea*) and *Cathaya* appear to be similar along the sections of Badenian age (Fig. 3).

5.2.2. Late Badenian–Sarmatian (Serravallian)

The rain and evergreen–deciduous mixed forest suffered a great transformation due to the loss and decrease in the abundance of several evergreen plants such as *Engelhardia*. This kind of vegetation was progressively substituted by deciduous and mesothermic plants, mainly deciduous *Quercus*, but also *Fagus*, *Alnus*, *Acer*, *Eucommia*, *Betula*, *Alnus*, *Carpinus*, *Ulmus*, *Zelkova*, *Tilia*, etc. Thus, the vegetation shows a tendency towards increasing proportions of mesothermic–deciduous elements coming from higher altitudes.

At the same time, the presence of altitude trees augmented therefore the vegetation from middle (*Cathaya*, *Tsuga* and *Cedrus*) and high altitude (*Picea* and *Abies*) belts clearly increased (Fig. 3).

This palaeofloristic change occurred gradually with cyclic fluctuations due to Milankovitch's astronomical forcing. These cyclic fluctuations were mainly related to the eccentricity and obliquity as shown by the analysis of the pollen time series of the Tengelic-2 core in a previous article (Jiménez-Moreno et al., 2005). A similar vegetation change is observed during the same timespan in other areas of Europe (e.g., southern France, Switzerland and Austria: Bessedik, 1985; Jiménez-Moreno, 2005).

5.3. Climatic variations during the late Early–Middle Miocene

5.3.1. Global climatic change: Monterey Cooling Event

Pollen results from these cores clearly reflect climate evolution from the late Burdigalian. The worldwide Miocene Climatic Optimum of the latest Burdigalian–early Langhian (equivalent to the Karpatian–early Badenian local stages) as well as a climatic cooling (the “Monterey cooling event”) which is related to the development of the East Antarctic Ice Sheet (Miller et al., 1991; Flower and Kennett, 1994; Zachos et al., 2001) and occurred during the late Langhian and Serravallian starting at 14.2 Ma (Shevenell et al., 2004) (middle and late Badenian–Sarmatian local stages) are well expressed by the pollen flora along the Tengelic-2 core (Jiménez-Moreno et al., 2005). In the Hidas-53 core these changes are evident only during the late Badenian

and early Sarmatian. This is maybe due to the overrepresentation of azonal elements reflecting local conditions during the Karpatian and early-middle Badenian.

5.3.2. Regional climatic change: palaeogeographic changes

The effects of the intense alpine tectonics during that time, generating the uplift of the Carpathians and the drifting of the Euroasiatic plate northward (Rögl, 1998; Meulenkamp and Sissingh, 2003), and the modification of the ocean heat transport from an antiestuarine situation to estuarine conditions in the Paratethys (Báldi, 2006) may have also contributed to the global climate dynamics that would increase the cooling in the European latitudes. Together, these would produce the same effect on the vegetation as the global climatic cooling, reducing thermophilous plants and increasing the presence of mesothermic–deciduous and altitude trees in the pollen spectra.

6. Conclusions

The palynological study on the Karpatian–Sarmatian part of the Hidas-53 and Tengelic-2 cores in Hungary has permitted the identification of a very rich and diverse flora which consisted of elements found presently in different geographic areas. The vegetation was characterized by a complex mosaic due to its dependency on several factors, being the most important factor, similar to present day, the altitude, controlling the temperature and precipitations.

The vegetation during the Karpatian and early-middle Badenian (late Burdigalian–Langhian) was dominated by thermophilous elements rich in evergreen trees such as *Engelhardia*, typical from a present day rain and evergreen forest at low altitudes. This kind of vegetation points to a subtropical climate for the Pannonian basin during the mentioned time-span and has been correlated to the warmest period during the Miocene: the Miocene climatic optimum.

During the late Badenian and Sarmatian (Serravallian) important changes in the vegetation are observed: several thermophilous elements, in which especially *Engelhardia*, strongly decreased, many of them disappearing from the central European area. The rain and evergreen–deciduous mixed forest suffered a great transformation due to the loss and decrease in the abundance of several evergreen plants. This kind of vegetation was progressively substituted by deciduous and mesothermic plants such as deciduous *Quercus*, and *Fagus*, *Alnus*, *Acer*, *Carpinus*, *Ulmus*, *Zelkova*, etc. At the same time, the presence of altitude trees increased. A progressive

climatic cooling is then interpreted. This cooling is universally known in the literature as the “Monterey cooling event” and is mainly related to an increase in the volume of the eastern Antarctic ice sheet but also related to the effects of the intense alpine tectonics during that time, generating the uplift of the Carpathians, the drifting of the Euroasiatic plate northward and the modification of the ocean heat transport. The effects that both global and regional processes produced on the vegetation are similar. Therefore they cannot be separated from one another using only pollen data.

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