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Pliocene and Lower Pleistocene vegetation and climate changes at the European scale: Long pollen records and climatostratigraphy

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A R T I C L E I N F O

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A B S T R A C T

The biostratigraphically calibrated long pollen record at DSDP Site 380 (southwestern Black Sea) displays a high-resolution continuous and contrasted evolution of the vegetation in the region for the entire Pliocene and Lower Pleistocene. An accurate correlation is established with the reference global oxygen isotopic curve and with the Northwestern European climatostratigraphy. Climatostratigraphic relationships are evident at the latitudinal and longitudinal scale of Europe, confirming the extensive strength of pollen analysis as a tool for correlations over large distances.

1. Introduction

This paper is dedicated to Waldo H. Zagwijn, in recognition of his impressive contribution to European climatostratigraphy.

The quest for long pollen sequences that provide a continuous record of vegetation and climate changes since the Early Pliocene started with Lona (1950) and Zagwijn (1960, 1975), and was continued by Menke (1975) and Wijmstra and Groenhart (1983) among others. Zagwijn was the first to establish a contrasted climatostratigraphy (from Brunssumian to Menapian for the time-interval on which this paper is focused, ca. 5.3–1 Ma). This paleoclimatical classification is still widely used today despite its weakness in independent chronological calibration (biostratigraphy, magnetostratigraphy). The Northwestern Mediterranean pollen diagrams (Autan 1, Garraf 1: Suc, 1984), biostratigraphically calibrated using foraminifera, established a reliable climatostratigraphic relationship between the Mediterranean and Northwestern Europe for the Pliocene and early Pleistocene (Suc and Zagwijn, 1983). However, insufficient sampling resolution of these pollen sequences did not result in an accurate correlation with the oxygen isotope stratigraphy. Recently, long high-resolution pollen records benefiting from an accurate time-control have been obtained for the Early Pliocene in southern Romania (Popescu, 2001; Popescu et al., 2006). Climatostratigraphic relationships were proposed with the corresponding interval of the deep Black Sea pollen record from the DSDP Site 380 (Popescu, 2006) a site that was lacking chronological constraints.

This paper presents new long pollen records from two boreholes, DSDP Site 380 (Black Sea) and Wólka Ligezowska (south Poland), separated by 9°30′ latitude (Fig. 1), continuously covering the entire Pliocene and more or less completely the Lower Pleistocene. The new Pliocene–Pleistocene boundary recently lowered to 2.588 Ma, which moves the Gelasian Stage at

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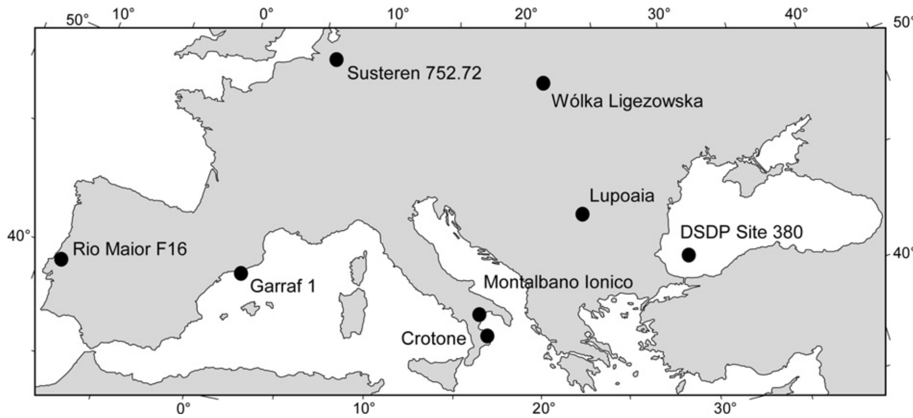

Fig. 1. Location map of site with pollen data used in this paper.

the base of the Pleistocene (Gibbard et al., 2010), and reduces the Pliocene to two stages only, the Zanclean and Piacenzian, is used. In addition, climatotratigraphy of these new pollen records is compared to that of other standard long pollen sequences (Fig. 1; Susteren 752.72 in The Netherlands: Zagwijn, 1960; Garraf 1 in the Northwestern Mediterranean: Suc, 1984; Rio Maior F16: Diniz, 1984). The comparison is extended to some other published Pliocene (Fig. 1; Lupoaia: Popescu, 2001; Popescu et al., 2006) and Early Pleistocene long pollen sequences (Fig. 1; Semaforo, Vrica and Santa Lucia sections from the Crotone area: Combourieu-Nebout, 1990, 1993; Joannin et al., 2007; Suc et al., 2010; and Montalbano Jonico: Joannin et al., 2008).

2. DSDP Site 380

2.1. Setting and previous chronostratigraphy

At Site 380 drilled at 2107 m water depth (Fig. 1; 42°05.94′N, 29°36.82′E), Pliocene deposits are considered to start at a depth of 864.50 m, i.e. just above the pebbly breccia (Hsü, 1978) which correlates to the Messinian Erosional Surface in the deep Black Sea (Gillet et al., 2007). Site 380 is very poor in Mediterranean microplankton (foraminfera: Gheorghian, 1978; nannofossils: Percival, 1978; diatoms: Schrader, 1978; dinoflagellate cysts: Popescu, 2006). However, a climatic subdivision of this sedimentary long record has been proposed by Hsü (1978) using the "Steppe Index" established by Traverse (1978) using pollen grains. A climatostratigraphic approach was detailed by Popescu (2006) for the lowermost 316 m of the series.

2.2. Towards an independent biostratigraphic calibration

The presence of marine microorganisms in some intervals of the series (diatoms: Schrader, 1978; calcareous coccoliths: Percival, 1978; dinoflagellate cysts: Traverse, 1978) required particular attention to the presence of marine dinoflagellate cysts during pollen counting process in order to optimize the selection of new samples which would possibly contain nannofossils. Seventeen levels were chosen (at metre depths: 219, 223.02, 326.14, 334.50, 368.43, 461.53, 471.50, 476.46, 504.35, 509.35, 518, 548.50, 586.49, 682.95, 708.20, 748.45, and 840.07). They correspond to warm phases in the pollen record, i.e. they correspond to global high sea-levels and, as a consequence might be good candidates for indicating temporary connections between the Mediterranean and Black seas. Eight of these samples (at 219, 223.02, 326.14, 368.43, 476.46, 504.35, 748.45, and 840.07 m depth) effectively provided nannofossil markers (Table 1).

Analysis of the new samples gave new chronologic constraints within Site 380 sediments using both (1) nannoplankton zonations (Table 1; Martini, 1971; Okada and Bukry, 1980) and (2) ages of the lowest occurrence (LO), highest occurrence (HO), lower consistent occurrence (LCO) and highest consistent occurrence (HCO) of the species indicated by Raffi et al. (2006):

- *Triquetrorhabdulus rugosus* and *Ceratolithus acutus* have been both recorded at 840.07 m depth. Accordingly this sample is between 5.345 Ma (*C. acutus* LO) and 5.279 Ma (*T. rugosus* HO) (early Zanclean);
- at 748.45 m depth, the presence of *Reticulofenestra pseudoumbilicus* indicates an age older than 3.839–3.79 Ma (*R. pseudoumbilicus* HO) (late Zanclean);
- at 476.46 m and 504.35 m depth, the presence of *Discoaster brouweri* indicates an age older than 2.06–1.926 Ma (*D. brouweri* HO) (late Gelasian);
- at 368.43 m depth, the presence of medium-sized *Gephyrocapsa* indicates an age younger than 1.73–1.67 Ma (medium-sized *Gephyrocapsa* spp. LO) (Calabrian);
- at 326.14 m depth, the presence of *Helicosphaera sellii* indicates an age older than 1.34–1.256 Ma (*H. sellii* HO) (Calabrian);
- the record of *Reticulofenestra asanoi* at depths 223.02 and 219 m indicates that these samples are between 1.136 Ma (*R. asanoi* LCO) and 0.901 Ma (*R. asanoi* HCO) (Calabrian).

2.3. Pollen record and climatostratigraphy

2.3.1. Materials and methods

Samples for pollen analyses were taken every 50 cm when available between 861.65 and 198.95 m depth. Twenty grams were processed following a standard method (Cour, 1974): acid digestion (HCl, HF), concentration techniques ($ZnCl_2$ at density 2.00, sieving at 10 μm), and mounting in glycerol for allowing rotation of pollen grains that improves their examination and hence their identification. At least 150 pollen grains (not including *Pinus)* were counted per sample. The analysis involves 691 samples which were rich enough in pollen grains. Taxa have been grouped according to their ecological significance (Suc, 1984; Popescu, 2006) and the results are first presented in a semi-detailed pollen diagram where curves are independent (Fig. 2), then in a synthetic pollen diagram where curves are combined (Fig. 3). Percentages have been calculated on the total of pollen grains for both pollen diagrams. Considering the advantage of the ratio between two climatically opposed plants or

Table 1
Nannoplankton content of the DSDP Site 380 studied samples with related nannoplankton zones (NN12 to NN19: Martini, 1971; CN10a to CN14a: Okada and Bukry, 1980) and stratigraphic ages. Crosses indicating abundant reworked specimens (from Cretaceous, Paleogene and Neogene) are shown in bold. Preservation of nannofossils is generally good except for depth 219 m (all material reworked?).

Age	Depth (m)	Nannoplankton Zones (Martini, 1971; Okada and Bukry, 1980)	*Amaurolithus primus*	*Braarudosphaera bigelowii*	*Calcidiscus leptoporus*	*Calcidiscus macintyrei*	*Ceratolithus acutus*	*Coccolithus pelagicus*	*Discoaster brouweri*	*Discoaster pentaradiatus*	*Discoaster triradiatus*	*Gephyrocapsa caribbeanica* (medium)	*Gephyrocapsa oceanica*	*Gephyrocapsa parallela* (large)	*Helicosphaera carteri*	*Helicosphaera sellii*	*Pontosphaera multipora*	*Pseudoaemiliania lacunosa*	*Reticulofenestra asanoi*	*Reticulofenestra pseudoumbilicus*	*Rhabdosphera clavigera*	Small reticulofenestrids	*Sphenolithus abies*	*Syracosphaera pulchra*	*Thoracosphaera* sp.	*Triquetrorhabdulus rugosus*	*Umbilicosphaera sibogae*	Reworked specimens
Calabrian	219.00	NN19 CN14a		X	X			X				X		X	X		X	X	X			X			X			**X**
	223.02	NN19 CN13b		X	X			X				X	X		X			X	X		X	X						**X**
	326.14				X			X				X	X		X	X	X	X			X	X			X			X
	368.43				X			X				X	X		X	X	X					X			X			X
Late Gelasian	476.46	NN18 CN12d			X	X		X	X		X				X	X	X				X	X			X			X
	504.35				X	X		X	X		X				X		X				X	X		X	X		X	X
Late Zanclean	748.45	NN13 CN10b-c			X	X		X	X	X					X		X			X		X	X	X	X		X	X
Early Zanclean	840.07	NN12 CN10a	X		X	X	X	X							X		X			X	X	X	X	X	X	X	X	X

groups of plants shown by Cour and Duzer (1978), the pollen ratio "thermophilous elements/steppe elements" has been calculated (Fig. 3): values <1 can be interpreted as indicating cooling phases, those >1 warming phases (see Suc et al., 2010).

2.3.2. Pollen flora

Forest components are, except for some rare megathermic trees, represented by mega-mesothermic elements (Taxodiaceae mainly with probable *Glyptostrobus*, *Engelhardia*, Sapotaceae, *Cathaya*, *Nyssa*, etc.) and mesothermic elements (*Quercus*, *Carya*, *Pterocarya*, *Liquidambar*, *Zelkova*, *Carpinus*, *Ulmus*, *Parrotia persica*, etc.). In contrast, herbs are dominated by Poaceae, Amaranthaceae-Chenopodiaceae and Asteraceae, among which *Artemisia* is abundant and is the main contributor to steppe vegetation. Microthermic (*Abies*, *Picea*) and meso-microthermic (*Cedrus*, *Tsuga*) trees are not very frequent, similarly to *Pinus* and the Mediterranean xerophytes (*Olea*, *Quercus ilex* type, etc.).

Taxodiaceae needs to be emphasized, taking into account the important place of this taxon along the section, particularly in the Early Pleistocene layers. From 599.30 m depth up to the top of the studied sediments, Taxodiaceae pollen grains show the same morphology (Fig. 4) and may be considered to correspond to the same taxon, probably the last surviving Taxodiaceae species in the region. A detailed comparison was performed at the scanning electronic microscope with pollen grains of the living genera and species of the family (Reyre, 1968; Jinxing and Yuxi, 2000). Taxodiaceae pollen grains of the upper part of the Site 380 are from a morphological point of view identical to those of the extant species *Glyptostrobus lineatus* (=*Glyptostrobus pensilis*) (Fig. 4). This is in agreement with the common evidence of *Glyptostrobus europaeus* macroremains in the Upper Neogene of the region (Kasaplıgil, 1977; Gemici et al., 1991; Ţicleanu, 1992; İnci, 2002). The last extant species *G. lineatus* grows in lowland swamps and riparian forests from northern Vietnam to southern China, where it is common in the river deltas in Guandong and Fujian (Wu and Raven, 1999). The last Taxodiaceae living in the Black Sea region during the Late Pliocene and Early Pleistocene, i.e. *Glyptostrobus*, occupied deltaic coastal areas suitable for ensuring pollen grain transport in large quantities down to the deep sea basin. As a consequence, the *Glyptostrobus* pollen grains recorded in interglacial deposits between 599.30 and 304.80 m depth may be over-represented, and the high-variability of tree and herb relative abundance somewhat exaggerated (Figs. 2 and 3).

2.3.3. Subdivisions of the pollen diagrams

This long pollen record shows fluctuations of variable amplitude that depict the continuous competition between forest

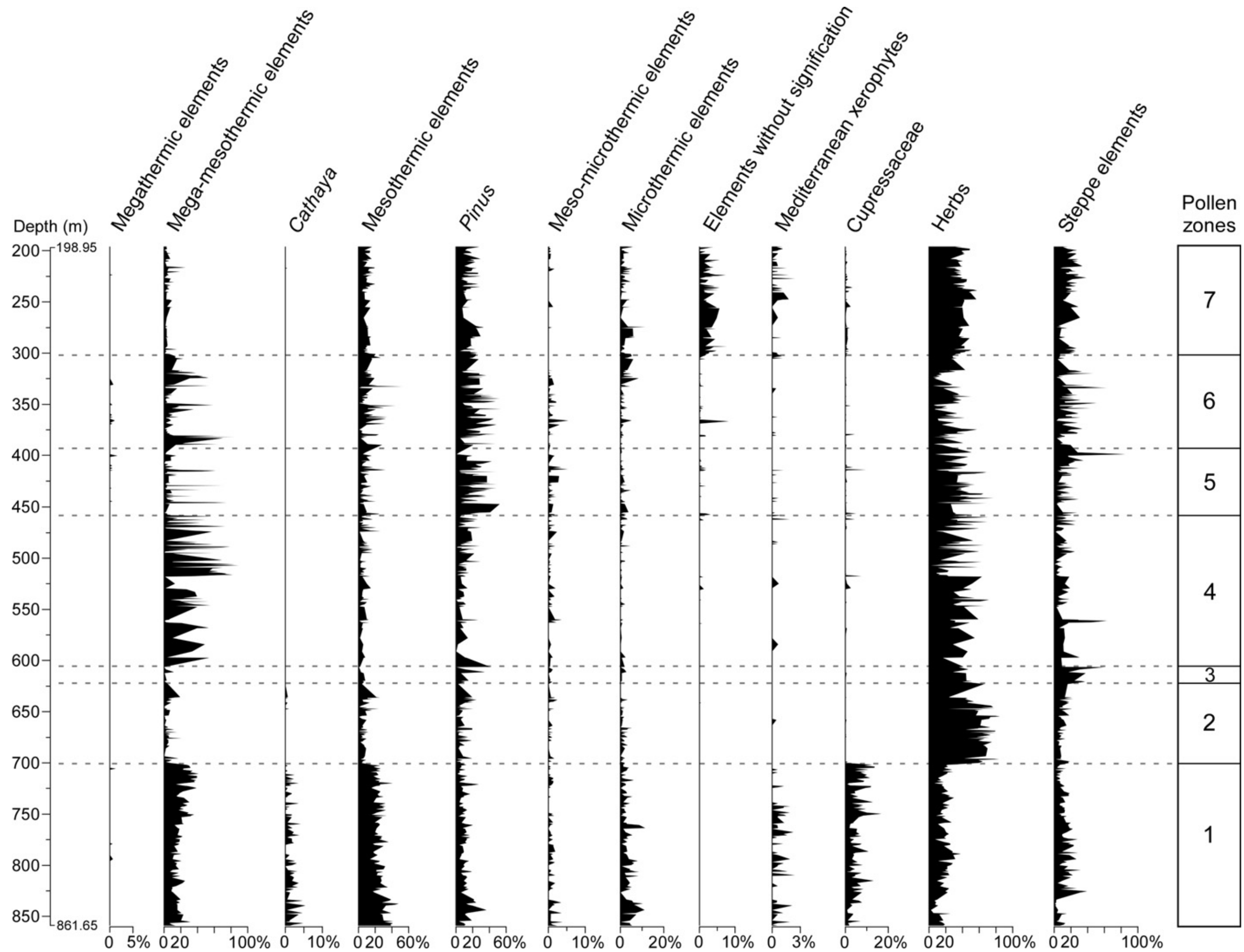

Fig. 2. Semi-detailed pollen diagram of DSDP Site 380 with the main pollen zones.

environments and open vegetation, as it is today in the area between forested coastal lands of Turkey and Bulgaria (relatively warm and humid climate) and the inner Anatolia steppes (cold and very dry climate) (Quézel and Barbero, 1985; Quézel and Médail, 2003). Seven major vegetation phases are recognized from the semi-detailed pollen diagram (Fig. 2) and are described hereafter. In addition, the establishment of the synthetic pollen diagram, in which relative fluctuations of the pollen groups are more easily decipherable, combined with the pollen ratio "thermophilous elements/steppe elements", confirms the seven major subdivisions and allows their subdivision (Fig. 3), as described below:

- Pollen zone 1 (861.65–702.80 m). Trees are prevalent with abundant mega-mesothermic and mesothermic elements, with Cupressaceae, *Cathaya* being almost continuously recorded (Fig. 2). This interval corresponds to extended forest environments on the Black Sea coastal plains due to warm and humid climate, while *Artemisia* steppe probably developed on the Anatolian Plateau in relation with drier conditions. Zone 1 is subdivided into three subzones (Fig. 3) as discussed by Popescu (2006):
  - a (861.65–814.40 m). Mega-mesothermic and mesothermic elements are prevalent, herbs and steppe elements show low percentages despite some isolated peaks. This episode corresponds to the first maximum extension of the forest with warm-moist climate temporarily affected by short cooling (and drying up) interval at 827–832 m.
  - b (814.40–727.60 m). Abundance of mega-mesothermic elements is lower, while that of herbs and steppe elements is higher. Forests are reduced and steppe is strengthened during this interval in relation with fluctuating less warm and humid conditions.
  - c (727.60–702.80 m). Mega-mesothermic elements, herbs and steppe elements show almost the same abundance as in subzone a. This phase displays the maximum development of forests and the minimum development of steppe. It is the warmest and most humid climatic phase recorded in the pollen diagram.
- Pollen zone 2 (702.80–624 m). Herbs with relatively low amounts of steppe elements are strongly dominant, while several mega-mesothermic elements and Cupressaceae are rare (*Cathaya*, Arecaceae, etc.) (Fig. 2). Open environments are developed except for the Anatolian *Artemisia* steppe. This denotes cooler but not very dry climatic conditions. Two subzones can be distinguished (Fig. 3):
  - a (702.80–655.20 m). Abundance of herbs is at maximum, that of trees minimum, except for some very brief peaks. *Artemisia* steppe shows very low percentages. Such a pollen flora indicates very open environments, as herbs are significantly under-represented in pollen records (Favre et al.,

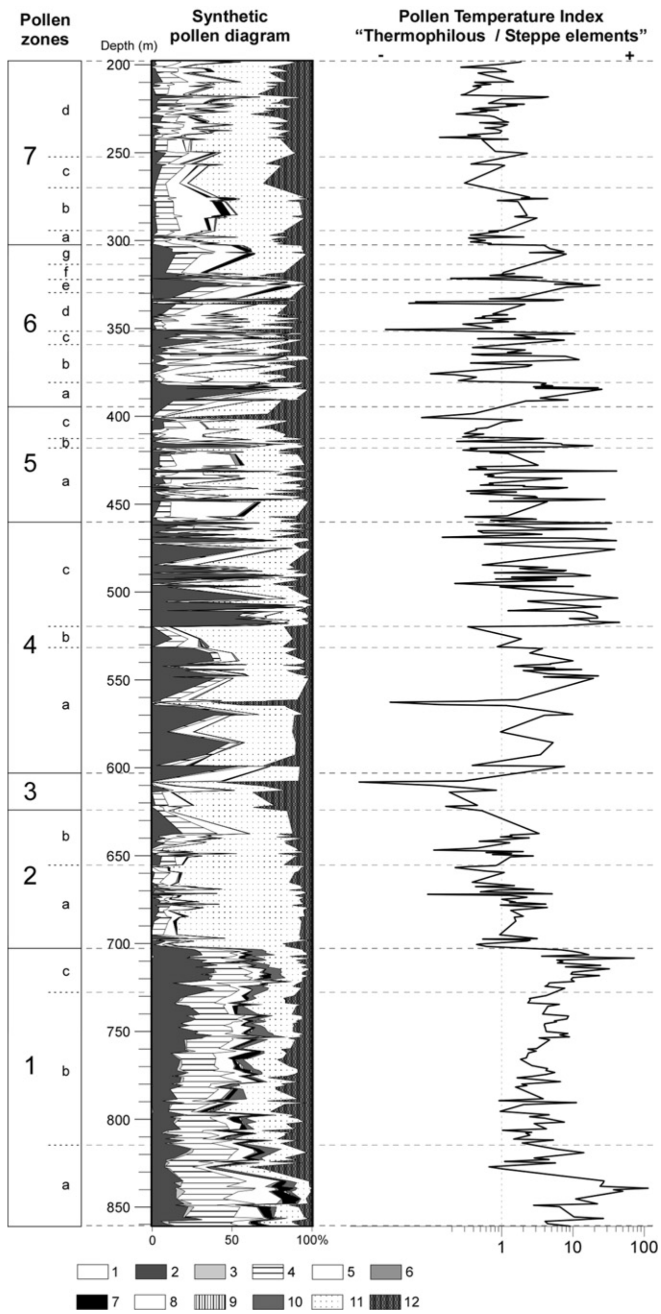

Fig. 3. Synthetic pollen diagram of DSDP Site 380 and pollen ratio "thermophilous elements/steppe elements" (plotted on a semi-logarithmic scale) with the main and secondary pollen zones. When the pollen ratio is >1: warming phase, when the pollen ratio is <1: cooling phase. Pollen groups (thermic classification: Nix, 1982): 1, Megathermic elements (*Buxus* colporate grains, *Canthium*, Acanthaceae, Sapindaceae, Sapotaceae, *Bombax*, etc.); 2, Mega-mesothermic elements (Taxodiaceae, Arecaceae, *Engelhardia*, *Platycarya*, *Distylium*, *Hamamelis*, *Microtropis fallax*, etc.); 3, *Cathaya*; 4, Mesothermic elements (*Quercus*, *Carya*, *Pterocarya*, *Liquidambar*, *Carpinus*, *Ulmus*, *Zelkova*, *Alnus*, *Buxus sempervirens*, etc.); 5, *Pinus*; 6, Meso-microthermic trees (*Cedrus*, *Tsuga*, *Keteleeria*); 7, Microthermic trees (*Abies*, *Picea*); 8, Elements without signification (Ranunculaceae, Rosaceae, indeterminate pollen grains); 9, Cupressaceae; 10, Mediterranean xerophytes (*Olea*, *Pistacia*, *Ceratonia*, *Quercus ilex* type, *Rhus* cf. *cotinus*, *Rhamnus*, *Cistus*, etc.); 11, Herbs (Amaranthaceae-Chenopodiaceae, Asteraceae, Poaceae, Apiaceae, *Rumex*, Borraginaceae, *Convolvulus*, Cyperaceae, *Helianthemum*, *Euphorbia*, Caryophyllaceae, etc.) including subdesertic elements (*Nolina*, *Lygeum*, *Neurada*, *Prosopis*, *Calligonum*, etc.) and water plants (*Alisma*, *Typha*, *Potamogeton*, *Myriophyllum*, etc.); 12, Steppe elements (*Artemisia*, *Ephedra*, *Hippophae*).

2008). Cooler and not very dry climatic conditions characterize this episode.

- b (655.20–624 m). Mega-mesothermic and mesothermic trees show almost continuously higher percentages as well as steppe elements, indicating less open vegetation and relatively warmer conditions.

- Pollen zone 3 (624–603 m). Very low percentages of mega-mesothermic and mesothermic elements characterize this interval in contrast to high percentages of herbs and the first high percentage of steppe elements (>25%) (Fig. 2). Very open vegetation and enlargement of the Anatolian *Artemisia* steppe probably was a response to a cooler and drier climate.
- Pollen zone 4 (603–460.30 m) is dominated by mega-mesothermic elements, especially Taxodiaceae which show their highest amount in the entire pollen diagram. They are probably almost completely composed of pollen grains from *Glyptostrobus*, a coastal tree (Section 2.3.2), significantly over-represented. Large amplitude fluctuations are observed and contrast thermophilous elements and herbs (without a significant steppe component, except for two peaks at the base). Phases dominated by herbs appear somewhat shorter than those dominated by thermophilous trees, which reach their maximum abundance in the entire pollen diagram (Fig. 2). Coastal forests strongly competed with inland open vegetation, probably a response to rapid climate fluctuations (warmer-moister phases opposed to cooler-drier ones), probably corresponding to glacial–interglacial cycles. Three subzones have been designated:
  - a (603–531.70 m). Maxima of thermophilous elements alternate with peaks of herbs with two peaks of steppe elements (Fig. 3). Competition is relatively balanced between coastal forests and inland open environments, illustrating the steady alternation of interglacial–glacial cycles.
  - b (531.70–519.95 m). This short episode is marked by very low values of thermophilous elements as opposed to the high values of herbs with little steppe elements (Fig. 3). Such a sudden opening of vegetation is related to a pronounced cooling without high dryness.
  - c (519.95–460.30 m). The largest repeated maxima of mega-mesothermic elements alternating with shorter maxima of herbs with moderate abundance of steppe elements (Fig. 3) document repeated closure-opening of the vegetation and large amplitude fluctuations in temperature and dryness.
- Pollen zone 5 (460.30–394.50 m) contrasts with the preceding zone by: (1) lower amounts of mega-mesothermic elements (except some peaks) and higher amounts of mesothermic elements, (2) longer temporal development of herbs with a higher frequency in *Artemisia* pollen at the end of the interval (Fig. 2). This illustrates the competition between weakly developed coastal and inner forests and open vegetation, characterized by a significant spread of the Anatolian *Artemisia* steppe. This evolution demonstrates shorter and cooler interglacials in opposition to longer, colder and drier glacials. Three subdivisions are proposed:
  - a (460.60–418 m). The development of *Pinus* weakens herb maxima which display moderate peaks of steppe elements (Fig. 3). Forest development is very weak during interglacials, *Pinus* and Taxodiaceae being probably over-represented. Open vegetation was prevalent during glacials but still important during interglacials. Temperature during interglacials was moderate in contrast to cold glacials, both characterized by not very dry conditions.
  - b (418–412.50 m). A brief but well-marked maximum in thermophilous elements characterizes this episode (Fig. 3)

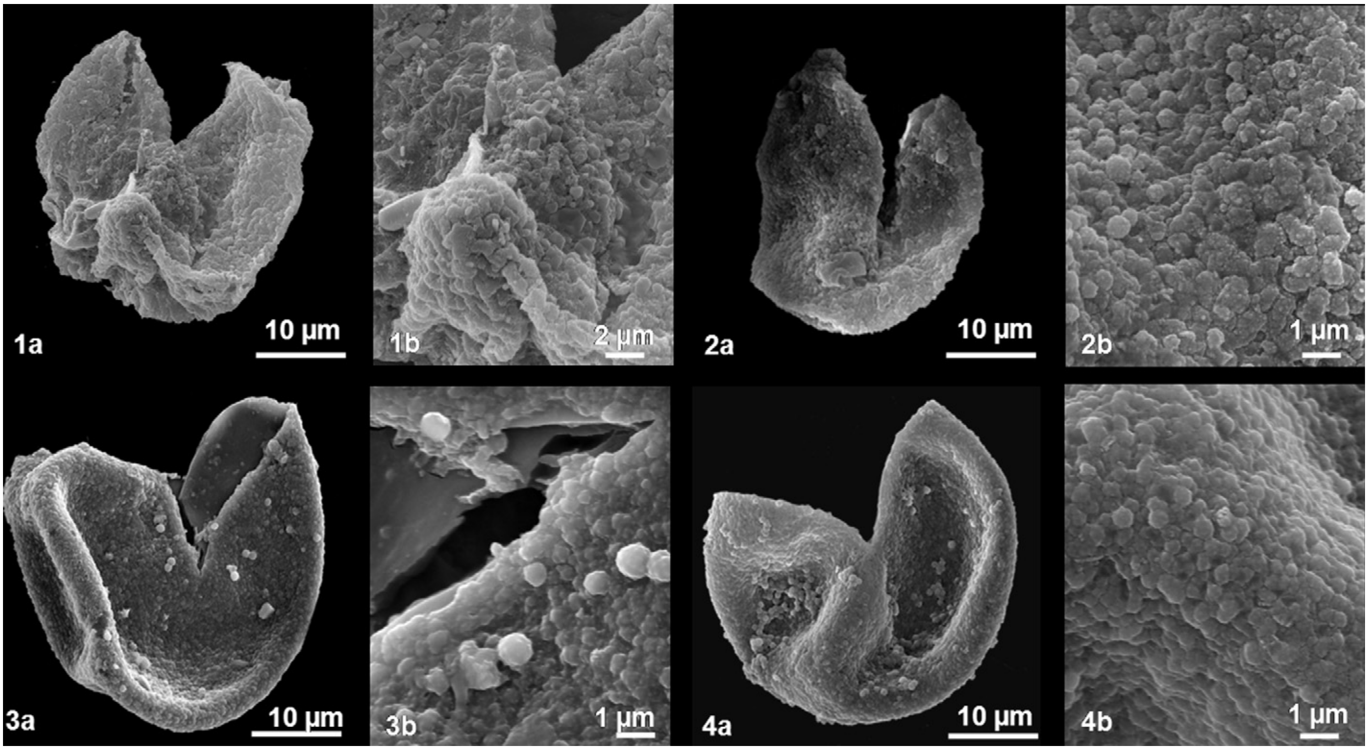

Fig. 4. Taxodiaceae pollen grains. 1. Pollen grain from Site 380 (448 m depth): a, General view showing the papilla (×2000); b, Detail of the sculpture in the papilla area (×6000). 2. Pollen grain from Site 380 (448 m depth): a, General view (×2000); b, Detail of the sculpture (×12000). 3 and 4. Two modern pollen grains of *Glyptostrobus pensilis* (Staunton ex D. Don) K. Koch, originating from China (Herbarium of the Sun Yat-sen University, Guangzhou; sample number: 28781; originating from the Herbarium of the Lingnam University, China): 3a, General view (×2000); 3b, Detail of the sculpture (×12000); 4a, General view of another grain (×2000); 4b, Detail of its sculpture (×12000).

which corresponds to a forest strengthening during a fluctuating interglacial.
- c (412.50–394.50 m). This interval shows the return to conditions of subzone 5a (Fig. 3) with more steppe elements and, as a consequence, drier conditions.

- Pollen zone 6 (394.50–302.40 m) shows increased thermophilous forest elements among which mesothermic trees became more important with strong repeated fluctuations between forest and open (with important steppe) environments (Fig. 2). This indicates large amplitude climatic fluctuations between interglacials and glacials. In detail, 7 subzones have been identified (Fig. 3):
  - a (394.50–380.07 m). Thermophilous elements, particularly the mega-mesothermic ones, are very abundant, indicating a pronounced interglacial episode.
  - b (380.07–359.30 m). Herbs and steppe plants prevail despite several moderate forest developments especially concerning mesothermic elements, denoting glacial–interglacial cycles characterized by lower temperatures.
  - c (359.30–351.60 m). Thermophilous elements are again dominant, indicative of an interglacial including some secondary coolings. Conditions appear less warm than during subzone a.
  - d (351.60–329.60 m). This is a well-marked steppe phase, i.e. cool and very dry conditions corresponding to a glacial event.
  - e (329.60–322.10 m). This is another forest interglacial phase almost similar to subzone 6a.
  - f (322.10–313.40 m). A maximum in herbs with abundant steppe elements at beginning characterizes this glacial phase.
  - g (313.40–302.40 m). Thermophilous trees increase again with a more important contribution of mesothermic elements during this distinctive interglacial.
- Pollen zone 7 (302.40–198.95 m). This zone is greatly dominated by herbs and steppe elements, the remaining thermophilous trees being henceforth mostly composed by the mesothermic elements (Fig. 2). Climatically, this zone corresponds to long severe climatic conditions interrupted by some short and weak improvements, allowing its subdivision in 4 subzones (Fig. 3):
  - a (302.40–294.40 m) represents a first intense maximum in herbs and steppe elements although two brief modest recoveries of thermophilous elements, as a response to a strong glacial.
  - b (294.40–269.90 m) corresponds to a low increase in mesothermic trees accompanied by *Pinus*. Herbs and steppe elements weakened, indicating a not very well pronounced interglacial.
  - c (269.90–252.40 m). Two important peaks of herbs and steppe elements alternate with a weak maximum in thermophilous elements, indicating improving conditions during a dominant glacial phase.
  - d (252.40–198.95 m). This last subzone is characterized by a large prevalence of herbs and steppe elements, punctuated by several small increases in thermophilous trees. It corresponds to dominant glacial phases interrupted by short interglacials.

2.3.4. Relationships with the oxygen isotope stratigraphy

Using the chronologic constraints provided by nannoplankton, these major phases and their subdivisions are correlated with Marine Isotope Stages (MIS) chosen on the basis of age control, general trends and amplitude of the respective fluctuations (Fig. 5).

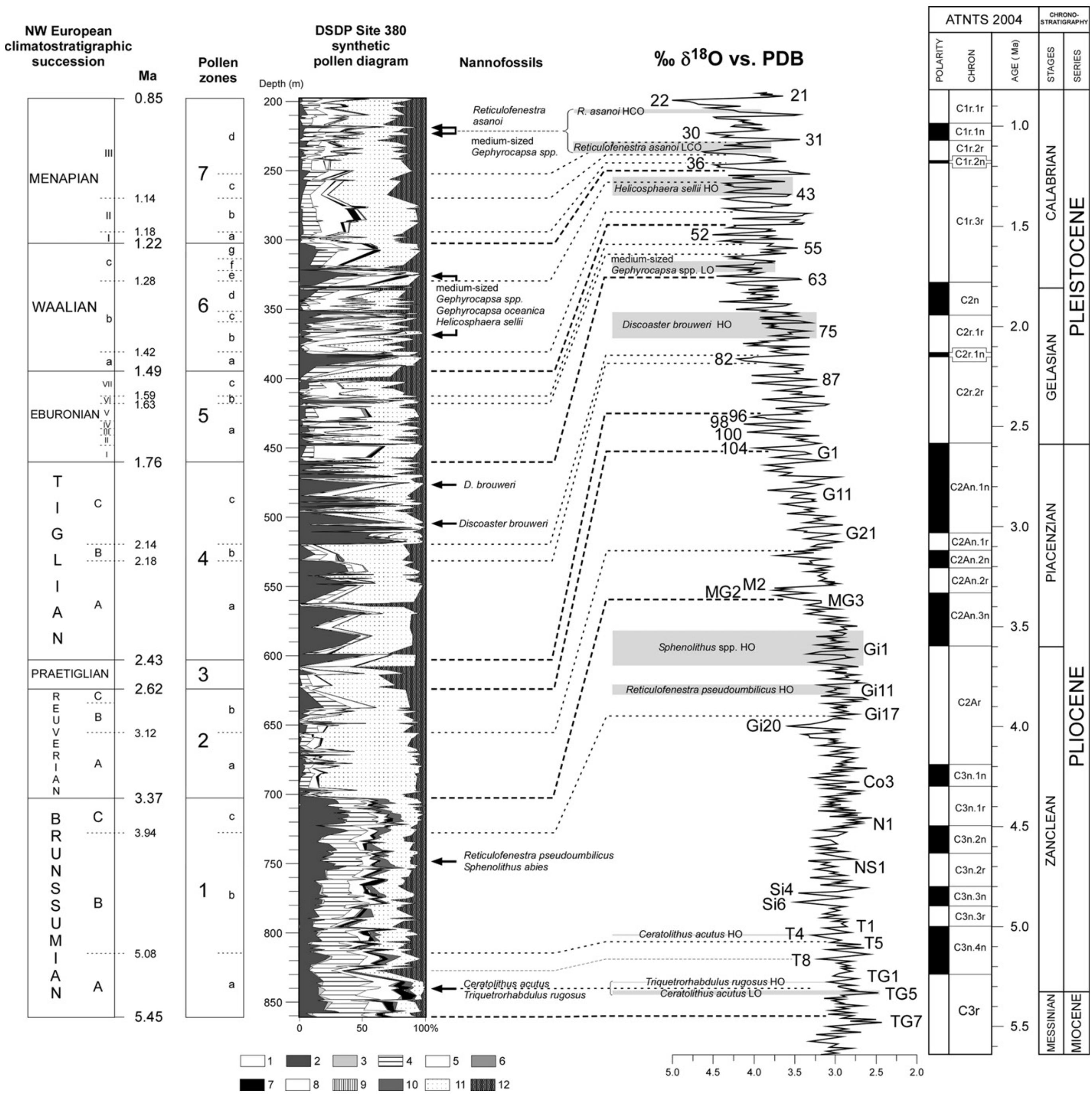

Fig. 5. Synthetic pollen diagram of DSDP Site 380 with detailed pollen zonation, localized nannoplankton evidences and proposed climatostratigraphic relationships with (1) the reference oxygen isotope curve (some Marine isotope Stages are plotted) (Shackleton et al., 1990, 1995) correlated with nannofossil biohorizons (Raffi et al., 2006), and (2) the NW European climatostratigraphic succession (Zagwijn, 1960, 1998). Nannofossil biohorizons: LO, Lowest Occurrence; HO, Highest Occurrence; LCO, Lowest Consistent occurrence; HCO, Highest Consistent Occurrence (Raffi et al., 2006). Chronostratigraphy (ATNTS 2004: magnetic reversals, stage boundaries) is from Lourens et al. (2004). Pollen groups: see Fig. 3.

This integrated approach led to an accurate age model of Site 380 (Fig. 5).

- Pollen zone 1. This warm phase was already referred to the Zanclean Stage by Popescu (2006). However, the evidence of nannofossils at 840.07 m implies a readjustment of the correlation to the oxygen isotope curve initially proposed by Popescu (2006). The oldest cooling event at 828.02 m does not correlate with MIS T4 but with MIS T8. Similarly, correlation of the preceding tree maxima with the $\delta^{18}O$ minima suggests that the oldest sample from aragonite is ca. 5.45 Ma old (i.e. older than the 5.327 Ma age previously proposed; Popescu, 2006). The end of pollen subzone 1a, i.e. pollen zone 4 in Popescu (2006), can be correlated with MIS T5, the end of pollen subzone 1b, i.e. pollen zone 5 in Popescu (2006), with MIS Gi19–Gi17.
- Pollen zone 2. The beginning and the end of this interval obviously correlate with MIS MG 2 (well-marked cooling) and MIS G1 just preceding the earliest glacial (MIS 104), respectively.
- Pollen zone 3. The three recorded peaks in herbs and *Artemisia* steppe are hence correlated to MIS cluster 104–100–98–96.

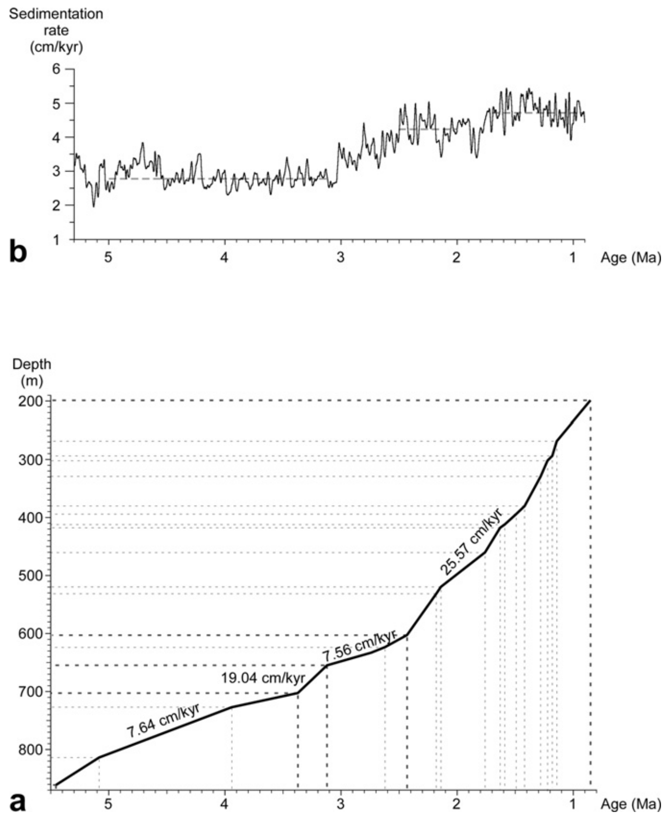

Fig. 6. Compared deep Black Sea and global ocean sedimentation rates. A. Sedimentation rate at Site 380 between 861.50 and 198.95 m depth. Coordinates of the inflection points are those indicated in the last column of Table 2 (thick dotted lines delimit intervals discussed in the text, with indication of the mean sedimentation rate of which). B. Global ocean sedimentation rate (Lisiecki and Raymo, 2005). The dotted line indicates the mean value for the three time-intervals 5–3.1 Ma, 2.5–2 Ma and 1.7–0.9 Ma.

One peak is missing in the pollen record probably because of an insufficient sampling resolution.

- Pollen zone 4. These fluctuations reflect short-term interglacial–glacial cycles (∼41 ky) within a relatively warm global context. It correlates to the MIS 95–63 interval. Fourteen of the seventeen known interglacials have been recorded in the pollen diagram despite the relatively low sample resolution in the lower half of the interval. Correlations can also be refined by identifying the brief cooling at 531.70–519.95 m (pollen subzone 4b) as the well-marked MIS 82.
- Pollen zone 5 is correlated to the MIS 62–50 interval, with the pollen subzone 5b corresponding to MIS 55.
- Pollen zone 6. This interval runs from MIS 49 to MIS 37, the limits between the main subdivisions (pollen subzones 6a–b and 6d–e) being located at transitions between MIS 47–46 and MIS 38–37, respectively. In addition, the pollen diagram displays almost the same number of fluctuations as the oxygen isotope curve for this interval.
- Pollen zone 7. This pollen zone is correlated to the oxygen isotope curve from MIS 36 to MIS 22, its fluctuations being possibly correlated to detailed isotopic stages (see for example MIS 35, very well-marked in the pollen diagram = pollen subzone 7b).

The age model of the 861.65–198.95 m depth interval of Site 380 allows reconstruction of the sedimentation rate in the deep Black Sea (Fig. 6A). The curve shows a first break at 3.37 Ma, i.e. 702.40 m in depth, which coincides with the observed opening of the vegetation (Fig. 3). Below this point, the slope of the curve is weaker (mean sedimentation rate: ca 8 cm/ky); above it, the sedimentation rate is almost two times higher (average: 19 cm/ky). It therefore records a significant increase in terrigenous material input around 3.4 Ma that might correspond to enhanced erosion related to the abrupt change from dominating trees to dominating herbs. The continuing open vegetation episode after 3.1 Ma up to 2.43 Ma (pollen subzone 2b and pollen zone 3) corresponds to a decrease in the sedimentation rate (Fig. 6A). The study of Pliocene – Pleistocene sedimentation rates from 57 globally spread ODP sites (Lisiecki and Raymo, 2005) showed an evolution of sedimentation rates from 2.5 to 3 cm/ky between 5 and 3.1 Ma, increasing to 4–4.5 cm/ky between 2.5 and 2 Ma and finally about 4.5 cm/ky between 1.7 and 0.9 Ma (Fig. 6B). The global oceanic sedimentation rate increased from Pliocene to Pleistocene. The same overall evolution is present in the Black Sea, but the initial increase seems to start a little earlier (3.4 Ma instead of 3.1 Ma in this case). The second increase is about the same date: 2.4 Ma in the Black Sea and 2.5 Ma in the global ocean, which is also the most commonly recognized timing for the initiation of Northern Hemisphere major glaciations. Values of average sedimentation rates are much higher in this case, because of the importance of fluvial inputs in the Back Sea.

The previous chronostratigraphy of Pliocene and Pleistocene sediments cored at Site 380, based on a low-resolution pollen record (Traverse, 1978), was already significantly modified for its lower part (861.65–704.34 m depth) by the high-resolution pollen record of Popescu (2006). The present results covering the entire Pliocene and Lower Pleistocene of this section significantly change the previous chronostratigraphy (Hsü, 1978; Muratov et al., 1978; Ross, 1978) and demonstrate the interest of high-resolution pollen analyses in the Black Sea.

Evidence of climate cycles (i.e. glacial–interglacial successions) in the Site 380 pollen record is apparent from 624 m depth (prevalent herbs and trees in turn) (Figs. 3 and 4). Despite an insufficient chronologic resolution in some parts of the pollen record through lack of available sediment, a detailed correlation with the reference isotope curve has been established. At the base (624 m depth), climate cycles clearly report the obliquity forcing (∼41 ky) resulting in fast and intense replacements in the vegetation and an almost equal duration of glacial and interglacial phases. Above 303 m depth (i.e. at about 1.22 Ma), the ∼41 ky signal attenuates, and the duration of cycles increases with longer glacials which is coherent with the installation of dominant ∼100 ky climatic cycles, i.e. the onset of the Mid-Pleistocene Revolution (Maslin and Ridgwell, 2005; Lisiecki and Raymo, 2007).

2.3.5. Relationships with the Northern Europe climatostratigraphy

The long–distance correlation reliability of Zagwijn's Pliocene and Early Pleistocene climatostratigraphy has been severely questioned. This climatostratigraphy effectively suffered from several handicaps, such as the lack in sedimentary continuity especially for the Pleistocene, the weakness of an independent chronostratigraphic calibration, and the low number of pollen samples (Donders et al., 2007; Kemna and Westerhoff, 2007; Westerhoff et al., 2008; Westerhoff, 2009).

However, the high-quality of pollen record of Site 380 and the great variability of the prevalent pollen groups undoubtedly allow its use as a reliable climatostratigraphic reference. Detailed comparison with the pre-existing Northern Europe climatostratigraphy (Zagwijn, 1960, 1963, 1975, 1985, 1998; Zagwijn and Suc, 1984) can be attempted (Fig. 5):

- Pollen zone 1. As already argued by Popescu (2006), this warm phase clearly corresponds to the Brunssumian of the NW

European climatostratigraphy, with two warm phases surrounding a less warm phase, respectively correlated with the three Brunssumian subdivisions.

- Pollen zone 2. This well-delimited episode is related to the Reuverian of the NW European climatostratigraphy, as it is a transitional interval between the last warm Pliocene event and the earliest glacials. It is made of two subzones:
  - subzone 2a, which reports the same temperature sequence as Reuverian A;
  - subzone 2b, which resembles Reuverian B by the same argument.

The transitional Reuverian C was not identifiable at Site 380 because there is an insufficient quantity of pollen grains between 638.20 and 625.35 m.

- Pollen zone 3. This first global cold interval corresponds to the Praetiglian, which is less homogenous than previously considered (cf. Suc and Zagwijn, 1983).
- Pollen zone 4. This zone immediately follows the earliest glacials. Accordingly, it is correlated with the “warm” Tiglian. Considering that the number of climatic fluctuations within the Tiglian was not definitely established as they have been regularly increased by new pollen data (see the increasing complexity of Tiglian A and, especially, Tiglian C in the successive Zagwijn papers), some correlations with the Tiglian three main subdivisions can also be suggested. On the basis of a rather robust correlation between pollen subzone 4b (well-marked cooling) with the “cold” Tiglian B, (1) the Site 380 subzone 4a can be correlated with Tiglian A, while (2) subzone 4c is correlated with Tiglian C, although the former is more subdivided.
- Pollen zone 5. This dominantly well-delimited “cold” phase is considered to correspond to the Eburonian. On the whole, subzone 5 displays numerous similarities with the Eburonian seven subdivisions (such as, for example, beginning and ending with a strong cooling). However, the significantly higher number of its fluctuations makes risky a detailed correlation with Eburonian. Only the pronounced interglacial of subzone 5b could be referred to Eburonian VI because of its location in the upper part of zone 5.
- Pollen zone 6. This zone contrasts with the previous one in indicating warmer conditions. Accordingly, it can be correlated with the Waalian, which is regarded as a dominantly “warm” phase. The two warmest episodes of zone 6 (subzone a on the one hand, subzones e–g on the second hand) sandwiching the complex subzones b–d can be compared with Waalian A and C, respectively.
- Pollen zone 7. Similar reasoning refers this zone to the Menapian, with two “cold” phases (subzones a and c–d) bordering a warmer one (subzone b regarded as equivalent of Menapian II).

This climatostratigraphic interpretation of the Site 380 pollen diagram not only provides a detailed age model for the considered section (Fig. 5) but also supports the large geographic scale reliability of the Zagwijn climatostratigraphy, at least concerning the main phases. In addition, the Site 380 climatostratigraphy clarifies the relationships of the Northern Europe climatostratigraphy and the oxygen isotope stratigraphy. Several authors, including Zagwijn himself (Zagwijn, 1975, 1998; Zagwijn and Suc, 1984; Kukla and Cilek, 1996; Leroy, 2007) have published calibrations and/or estimates of the age of some of the climatostratigraphic unit boundaries (Table 2). On the whole, taking also into account the numerous modifications of the Global Polarity Time Scale over the last decades, most of these ages are consistent with the ages provided by correlation of pollen fluctuations documented here with the reference oxygen isotope curve. More precisely, the ages indicated by Zagwijn (1998) and Leroy (2007) are very close to these ages (Fig. 5; Table 2).

In addition, the ratio between “thermophilous elements/steppe elements” from Site 380 (Fig. 3) constitutes a temperature curve which resembles that published by Zagwijn (1998) for The Netherlands, especially concerning the climate megaphases (pollen zones 1 to 7), especially those encompassing glacial–interglacial cycles. Phases corresponding to a global cool to cold context (pollen zones 3, 5 and 7; i.e. Praetiglian, Eburonian, Menapian) have glacials (prevalent herbs) more marked than interglacials (dominant trees). Phases corresponding to warm contexts (pollen zones 4 and 6; i.e., Tiglian and Waalian) have interglacials (prevalent trees) more marked than glacials (dominant herbs).

2.3.6. Spectral analysis

The relationship with astronomical cycles was used as a base for a spectral analysis after grouping the pollen zones into three parts (Fig. 7):

- lower part: pollen zones 1–2 (861.65 m–624 m; 5.45–2.62 Ma) prior to the onset of glacial–interglacial cycles;
- middle part: pollen zones 3–6 (624 m–302.40 m; 2.62–1.22 Ma) when short-term glacial–interglacial cycles (~41 ky) dominated;
- upper part: pollen zone 7 (302.40–198.95 m depth; 1.22–0.85 Ma) when long-term glacial–interglacial cycles (~100 ky) started.

Generally, due to differences in the number of samples considered (upper part: 129; middle part: 560; lower part: 1132), the significance of the spectral analysis is higher in the lower part of the section, a fact that can also be read from the width of the respective confidence intervals – the smaller the confidence interval, the higher the significance of the analysis.

Analysis of the lower part relies on the highest number of assemblages and is related to the highest significance, i.e. to the smallest confidence intervals. Accordingly, although a weak ~41 ky obliquity cycle exists, the spectral bands are dominated by multiple ~21–23 ky precession cycles. The ~100 ky cycle signal is represented only by 6 out of 34 plant taxa, i.e. Asteraceae Asteroideae, Cupressaceae, Cyperaceae, Poaceae, *Carya*, and *Quercus ilex*.

Significant information is provided for the middle part, yielding a stronger influence of the ~100 ky cycle and the ~41 ky obliquity cycle (especially when considering the representative taxa). In addition, the multiple ~19–21 ky and ~21–23 ky precession periodicities can be observed across all taxa analysed. A more distinguished view on the ~100 ky cycle is given by comparing those taxa which respond to this orbital signal with those, due to their physiology or environmental requirements, which are not influenced. Ranunculaceae, *Artemisia* and Asteraceae Asteroideae clearly respond to the ~100 ky cycle, whereas *Pinus*, Asteraceae Cichorioideae, Caryophyllaceae, Brassicaceae, and deciduous *Quercus* have no affinity (number of non-zero entries are equivalent).

Although the significance is comparatively low, the upper part reveals that vegetation largely responded to ~100 ky climatic cycles as a multiple ~19–23 ky precession periodicity. The ~100 ky cycle is best reflected by Amaranthaceae-Chenopodiaceae, Asteraceae Cichorioideae, and *Carpinus betulus*, whereas Rosaceae and *Betula* do not show any affinity to the long climatic cycles. Interestingly, Ranunculaceae is the only taxon which indicates the occurrence of a weak ~41 ky cycle.

Table 2
Proposed ages in Ma (Zagwijn, 1960, 1998; Zagwijn and Suc, 1984; Kukla and Cilek, 1996; Leroy, 2007) for some limit boundaries of the NW Europe climatostratigraphic subdivisions. Some of them (base of Praetiglian, Eburonian and Menapian) have been calibrated on the basis of paleomagnetic reversals (Van Montfrans, 1971; Zagwijn, 1975). For most of the limit boundaries of the NW Europe climatostratigraphic subdivisions, the proposed ages in this paper are extrapolated from the climatostratigraphic interpretation of the Site 380 pollen record.

NW EUROPE CLIMATOSTRATIGRAPHY	Zagwijn (1975)	Zagwijn and Suc (1984)	Kukla and Cilek (1996)	Zagwijn (1998)	Leroy (2007)	This paper
BAVELIAN						
	~0.72	~1.0		~1.07	~1.05	0.85
MENAPIAN III						
						1.14
MENAPIAN II						
						1.18
MENAPIAN I						
	0.9	1.2	~1.12	~1.25	~1.25	1.22
WAALIAN c						
		~1.25				1.28
WAALIAN b						
		~1.3				1.42
WAALIAN a						
		~1.4		~1.5	~1.45	1.49
EBURONIAN VII						
						1.59
EBURONIAN VI						
						1.63
EBURONIAN I - V						
	1.7	1.6	~1.56	1.75	1.7	1.76
TIGLIAN C						
		~1.8		~2.0		2.14
TIGLIAN B						
		~1.9		~2.12		2.18
TIGLIAN A						
	~2.2	~2.1		~2.25	~2.25	2.43
PRAETIGLIAN						
	2.6	2.3	~2.19	2.5	2.45	2.62
REUVERIAN C						
		~2.45		~2.6		
REUVERIAN B						
		~2.7		~3.0		3.12
REUVERIAN A						
		~3.2				3.37
BRUNSSUMIAN C						
		~3.75				3.94
BRUNSSUMIAN B						
		~4.05				5.08
BRUNSSUMIAN A						
		~5.2				5.45
SUSTERIAN						

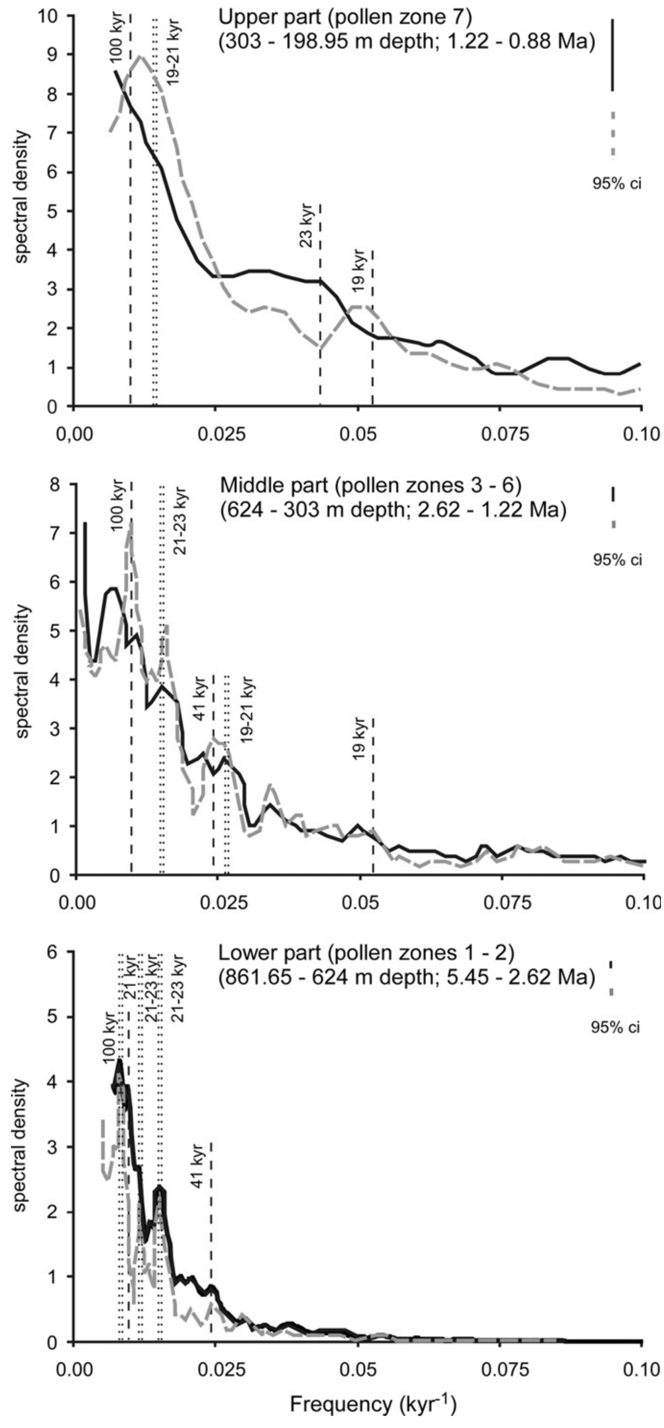

Fig. 7. Power spectra calculated for Site 380 using fast Fourier transformation (5% tapered, 7 band Tukey-window, confidence intervals for the upper, middle and lower parts of the pollen record. Solid black lines representing the average power spectra calculated on taxa with more than 40% non-zero entries in the respective section. Dotted grey lines representing the average power spectra calculated on three taxa representative of the pollen zonation: these are for the lower part Amaranthaceae, *Acer*, *Picea*; for the middle part Asteraceae Cichorioideae, Ranunculaceae, *Carpinus orientalis*; and for the upper part Amaranthaceae, Asteraceae Cichorioideae, *Carpinus orientalis* (for better representation spectral density is multiplied with factor 3 for all parts). Vertical dashed lines indicate the major cycles, vertical double dotted lines represent multiples of the major cycles.

3. Wólka Ligezowska

The Wólka Ligezowska (Poland: 51°35′N, 20°35′E) pollen record comes from cored sediments (39.50 m in depth) through a paleolake in the southern part of the Mazovian Lowland. The studied sediments (from 34.50 to 10.15 m depth) consist of silts, clays, gyttjas and sandy layers interrupted by peat layers (Jakubowicz et al., 1994). These sediments belong to the Polish "pre-glacial complex" the age of which is now accepted to be Pliocene and Early Pleistocene on the basis of palynostratigraphy (Baraniecka, 1991; Stuchlik, 1994).

3.1. Material and methods

A total of 113 samples were processed in 10% HCl and then boiled in 10% KOH. They were treated with heavy liquid in order to remove the mineral fraction, and finally the Erdtman (1969) acetolysis method was applied.

At least 250 pollen grains were counted per sample, but usually 1000 (sometimes 500 pollen grains of trees and shrubs). Results are presented in a semi-detailed pollen diagram (with independent curves) where taxa have been grouped according to their ecological significance, and in a synthetic pollen diagram (combined curves) (Fig. 8). Calculation of pollen percentages was based on the total number of pollen grains.

3.2. Vegetation changes and subdivisions of the pollen diagrams

The relative distribution of the main groups in the semi-detailed pollen diagram results in identification of 3 pollen zones. The synthetic pollen diagram allows further subdivision of pollen zones 1 and 2 in three subzones, respectively (Fig. 8).

- Pollen zone 1 (34.50–25.90 m). This interval suggests that plant ecosystems were connected with wet habitats:
  - swamp forest with *Alnus, Nyssa,* Taxodiaceae, Cupressaceae, *Carya* and *Pterocarya*;
  - marshes inhabited by shrubby *Salix* and *Myrica,* dwarf shrubs represented by Ericaceae, accompanied by Poaceae and Cyperaceae as main components of herbs;
  - meso-hygrophilous forest dominated by *Ulmus, Pterocarya, Liquidambar, Fraxinus Carya* and *Juglans* in the drier areas.

The deciduous forest community was composed of mesothermic taxa such as *Quercus, Castanea, Ilex* (represented by pollen grains of *Ilex aquifolium* and *Ilex margaritatus* types), *Eucommia, Aesculus, Liriodendron, Magnolia, Parrotia persica*, *Carpinus, Tilia, Fagus*, and *Acer. Pinus, Picea, Abies* and *Tsuga* are in low frequencies and suggest that colder conditions existed in the region. Variability of *Sequoia* type expresses changes both in humidity and temperature. Such arboreal pollen assemblages indicate a warm-temperate and humid climate at low altitude. However, the regular occurrence of *Itea*, a mega-mesothermic element, is notable.

Three subzones have been identified:

- a (34.50–30.15 m). It is characterized by abundant mega-mesothermic elements, and is the oldest warm phase in the pollen record.
- b (30.15–27.34 m). This phase indicates some cooling as expressed by a decrease in mega-mesothermic elements and an increase in mesothermic elements over *Pinus sylvestris* type and herbs.
- c (27.34–25.90 m). Mega-mesothermic are abundant, making this phase the youngest warm one in the pollen record.
- Pollen zone 2 (25.90–17.60 m). The gradual decrease in thermophilous elements and disappearance of those characterizing humid climate and their replacement by *Quercus* might indicate more continental climatic conditions (increasing dryness and decreasing temperature). Larger percentages of

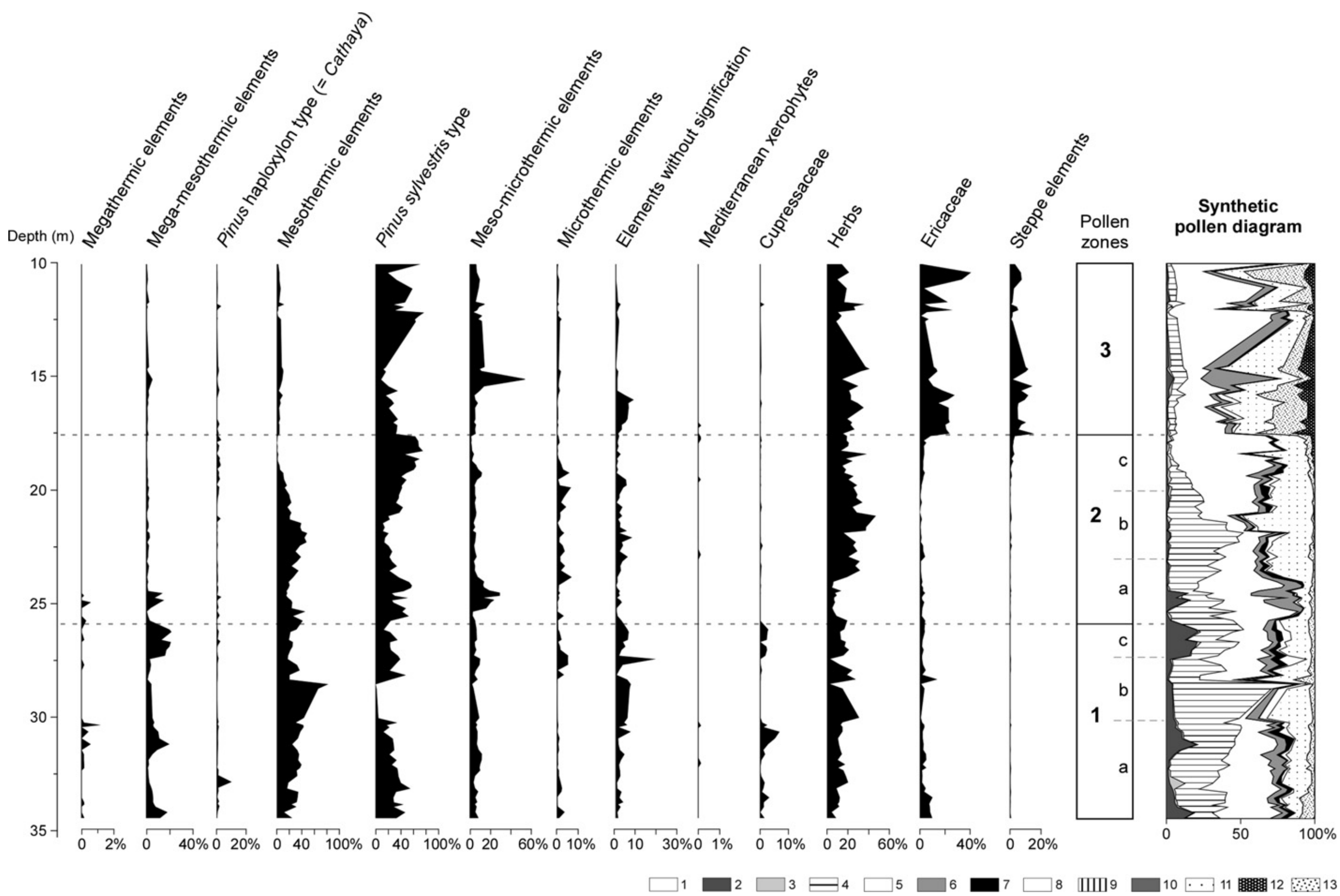

Fig. 8. Semi-detailed and synthetic pollen diagrams of Wólka Ligezowska borehole with pollen zonation. Pollen groups (thermic classification: Nix, 1982): 1, Megathermic elements; 2, Mega-mesothermic elements; 3, *Pinus* haploxylon type (=*Cathaya*); 4, Mesothermic elements; 5, *Pinus sylvestris* type; 6, Meso-microthermic trees; 7, Microthermic trees; 8, Elements without signification; 9, Cupressaceae; 10, Mediterranean xerophytes; 11, Herbs; 12, Steppe elements; 13, Ericaceae.

herbaceous pollen and their higher diversity (Poaceae, Cyperaceae, Asteraceae, Oenotheraceae, Brassicaceae, *Lythrum, Rumex acetosa* type, *Polygonum persicaria* type, etc.) show the development of varied communities in open habitats. *Phlomis, Cistus, Medicago* and Malvaceae (*Lavatera*) pollen grains occur in small amounts.

This zone has been subdivided into three subzones:

- a (25.90–23.02 m). It displays several fluctuations with a first development of *Alnus* (mesothermic tree) followed by a well-marked strengthening of *Betula* (meso-microthermic tree) alternating with the last peaks of mega-mesothermic trees (*Nyssa* and *Sequoia* type), and finally an increase in *Quercus* (mesothermic tree), *Pinus sylvestris* type and herbs. Climatically, this evolution expresses a weak cooling, then alternating warmer and cooler conditions, and finally less humid ones.
- b (23.02–20.07 m). Large amounts of Poaceae (herbs) contrast with those of *Quercus* (mesothermic tree) according to variability in *Pinus sylvestris* type, illustrating temperate conditions with fluctuating humidity.
- c (20.07–17.60 m). *P. sylvestris* type frequency increases, suggesting the development of an open pine forest, while herbs (Poaceae and Cyperaceae mostly) remain abundant and *Quercus* becomes rare. Probably, the climate conditions weakened with a drop in winter and summer temperatures and decreased precipitation.
- Pollen zone 3 (17.60–10.15 m). The strong expansion of herbs and dwarf shrubs documents the onset of severe cooling (earliest glacials). The vegetation was dominated by Poaceae, Cyperaceae, various species of *Artemisia*, and Ericaceae including *Bruckenthalia* and *Calluna vulgaris.* Typical heliophytes such as *Ephedra, Helianthemum, Thalictrum, Plantago* and *Gypsophila* were commonly recorded. The rich taxonomic composition reflects a considerable variety of plant communities in a humid tundra-like vegetation (dominant Cyperaceae) including dwarf shrubs (Ericaceae, *Betula nana*) and some drier assemblages (Poaceae, *Artemisia*, Chenopodiaceae). Some improvements in temperature and decrease in moisture are indicated by *Pinus sylvestris* type indicating some reappearance of forest areas (tundra-park) in opposition to typical tundra phases (Ericaceae, Poaceaae, Cyperaceae and *Artemisia* growths).

3.3. Relationships with the Northwestern European climatostratigraphy

The earliest development of tundra-like vegetation in the upper part of the Wólka Ligezowska pollen record establishes the Pliocene age of the underlying sediments. As the changes in vegetation pointed out by the Wólka Ligezowska pollen diagrams are apparent and significant, a direct climatostratigraphic relationship can be reliably proposed with the Northwestern European chart (Zagwijn, 1998) as shown on Fig. 9. Pollen zone 1, the forest lower phase rich in thermophilous trees, correlates with the Brunssumian with consistent subdivisions (a slightly cooler phase, subzone b, sandwiched between the two warmest phases of the pollen record, pollen subzones a and c). The overlying pollen zone 2, dominated by mesothermic elements, relates to the Reuverian, including the respective subdivisions: two cyclic climatic phases, pollen subzones a and b (at a lesser thermic level), preceded the transitional episode of pollen subzone c which is accordingly related to Reuverian C. The tundra-like following pollen zone 3 is connected with the Praetiglian and displays fluctuations.

4. Synthesis at the European scale

Concerning the Pliocene and earliest Pleistocene, climatostratigraphic relationships may be established between DSDP Site 380 and the Northwestern European climatostratigraphy (Zagwijn, 1998) as well as for the Wólka Ligezowska pollen record for the Pliocene and earliest Pleistocene (Brunssumian to Praetiglian) (Fig. 9). Similar reliable relationships have already been proposed for the Early Pliocene (Zanclean and early Piacenzian) between Site 380, Garraf 1(Suc, 1984), Susteren 752.72 (Zagwijn, 1960) and Rio Maior F16 (Diniz, 1984) by Popescu (2006) despite the low-resolution of the three last pollen records (Fig. 9). Such climatostratigraphic relationships can be also tentatively extended to the Late Pliocene (Piacenzian) and Early Pleistocene (earliest Gelasian) (Fig. 9). The base of the Praetiglian (MIS 104) has been plotted on each pollen diagram where the most important break in vegetation is recorded (development of tundra-like environment in The Netherlands and Poland, *Artemisia* steppe in the Mediterranean region *s.l.*, Cupressaceae woodland in Portugal). Each bioclimatic province specifically responded to the successive changes in climate according to latitude, longitude and regional features (Suc et al., 1995; Suc and

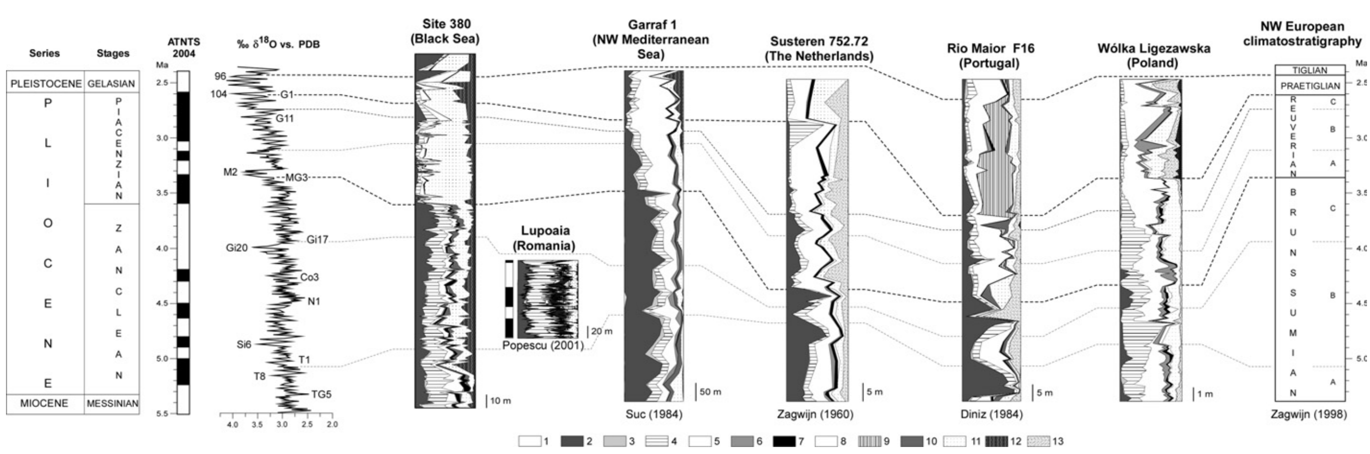

Fig. 9. Climatostratigraphic correlations for the Pliocene and earliest Pleistocene (1) between the synthetic pollen diagram of Site 380, Lupoaia, Garraf 1, Susteren 752.72, Rio Maior F16, and Wólka Ligezowska, (2) with the NW European climatostratigraphic succession (Zagwijn, 1998), and (3) the reference oxygen isotope curve (some Marine Isotope Stages are plotted) (Shackleton et al., 1990, 1995). Chronostratigraphy (ATNTS 2004: magnetic reversals, stage boundaries) is from Lourens et al. (2004). Magnetostratigraphy performed at Lupoaia is indicated (Popescu, 2001). Pollen groups (thermic classification: Nix, 1982): 1, Megathermic elements; 2, Mega-mesothermic elements; 3, *Cathaya* (= *Pinus* haploxylon type at Wólka Ligezowska); 4, Mesothermic elements; 5, *Pinus*; 6, Meso-microthermic trees; 7, Microthermic trees; 8, Elements without signification; 9, Cupressaceae; 10, Mediterranean xerophytes; 11, Herbs; 12, Steppe elements; 13, Ericaceae.

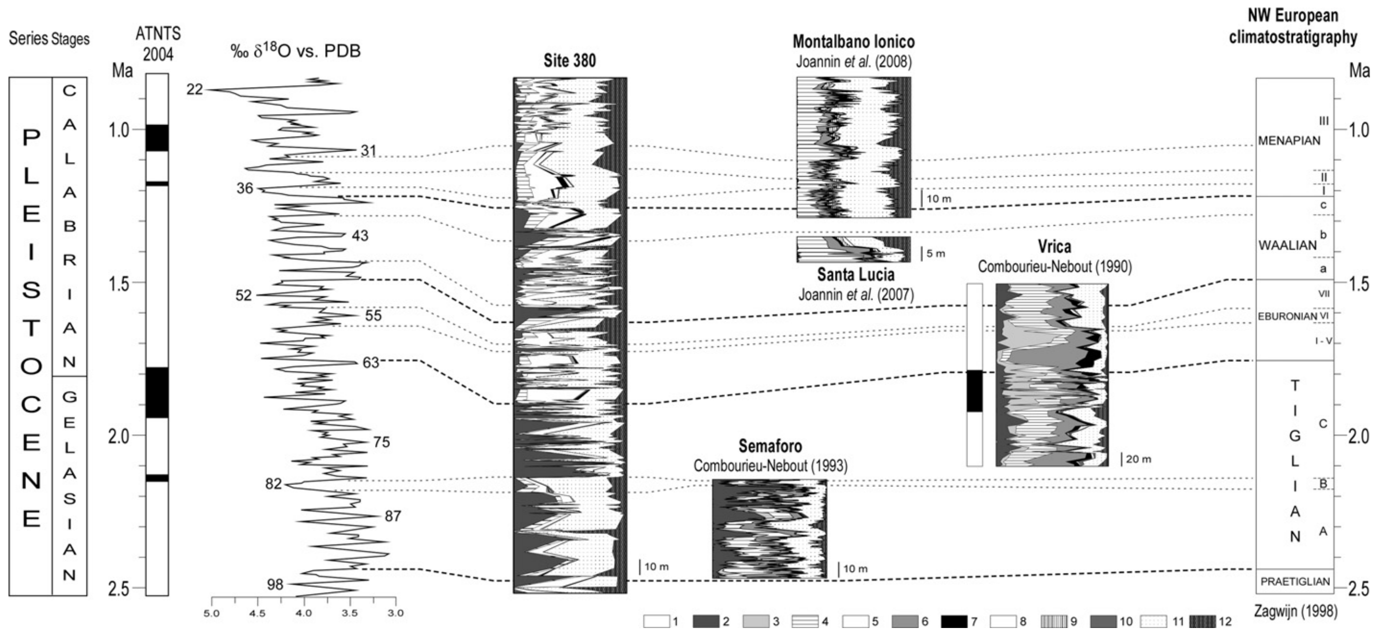

Fig. 10. Climatostratigraphic correlations for the Lower Pleistocene (1) between the synthetic pollen diagram of Site 380, Semaforo, Vrica, Santa Lucia and Montalbano Ionico, (2) with the NW European climatostratigraphic succession (Zagwijn, 1998), and (3) the reference oxygen isotope curve (some Marine Isotope Stages are plotted) (Shackleton et al., 1990, 1995). Chronostratigraphy (ATNTS 2004: magnetic reversals, stage boundaries) is from Lourens et al. (2004). Magnetostratigraphy performed at Vrica is indicated (Zijderveld et al., 1991). Pollen groups: see Fig. 3.

Popescu, 2005). The most intense regional differentiation in vegetation characterizes the Praetiglian phase whereas the Brunssumian phase is much more homogeneous. The climatostratigraphic correlation of the Lupoaia section with the Brunssumian subdivisions has been slightly modified (Fig. 5) from the earlier interpretation (cf. Popescu, 2006).

A comprehensive climatostratigraphic calibration of the Mediterranean pollen records was established by Suc and Popescu (2005) with a precise correlation to the oxygen isotope stratigraphy of several pollen localities. The results from the calibrated Site 380 offers the opportunity to correlate this record with the southern Italian long pollen records representative of the almost entire Gelasian and Calabrian stages (Crotone: Semaforo, Vrica, Santa Lucia; Combourieu-Nebout, 1990, 1993; Joannin et al., 2007; Montalbano Ionico: Joannin et al., 2008) giving an extended Northwestern European climatostratigraphy framework (Fig. 10). As *Pinus* is very abundant in Semaforo, Vrica, Santa Lucia and Montalbano Ionico pollen floras, the corresponding synthetic pollen diagrams have been established without this taxon. This allows a more distinct display of climatic fluctuations (percentages are calculated on the total of pollen grains minus those of *Pinus*). The major NW European climatostratigraphic subdivisions (Tiglian, Eburonian, Waalian, Menapian) can be recognized in the southern Mediterranean sections. The secondary climatic phases of NW Europe are more difficult to recognize, because the large amplitude of the ∼41 ky forced "glacial–interglacial" fluctuations somewhat hides them. However, they can be delimited using the relevant calibration of the South Mediterranean sections with the marine isotopic stratigraphy (Fig. 10). As does the uppermost part of Site 380, the pollen diagram of Montalbano Ionico shows the replacement of ∼41 ky climate cycles by ∼100 ky ones (Joannin et al., 2008).

5. Conclusion

Thanks to the contrasted images of the vegetation that it displays, the high-resolution pollen record of the entire Pliocene and Lower Pleistocene at DSDP Site 380, biostratigraphically well-calibrated through nannoplankton, allows a continuous, accurate and robust relationship with the reference oxygen isotope curve and the Northwestern European climatostratigraphy. Pollen records at Site 380 and Wólka Ligezowska, obtained in very different paleo-vegetation contexts, both corroborate the reliability of the Northwestern European climatostratigraphy, supporting its value as a direct response to past climatic changes. All the main subdivisions of the Northwestern European climatostratigraphy and most of the secondary ones can be identified in the Northern Hemisphere long pollen records, confirming the strength of this tool.

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