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Published version:

DOI:10.1016/j.palaeo.2015.09.038

TEODORIDIS, V., BRUCH, A.A., VASSIO, E., MARTINETTO, E., KVAČEK, Z., STUCHLIK, L., 2015 in press. Plio-Pleistocene floras of the Vildštejn Formation in the Cheb Basin, Czech Republic – a floristic and palaeoenvironmental review, Palaeogeography, Palaeoclimatology, Palaeoecology.

doi: http://dx.doi.org/10.1016/j.palaeo.2015.09.038

Plio-Pleistocene floras of the Vildštejn Formation in the Cheb Basin, Czech Republic – a floristic and palaeoenvironmental review

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Abstract

Fossil plant assemblages (foliage, fruits and seeds, pollen, wood) from the Pliocene and early Pleistocene deposits in W Bohemia (the Vildštejn Formation of the Cheb Basin, Tachov /Cheb–Domažlice/ Graben) are newly analysed using several palaeoenvironmental methods aiming at reconstructing palaeovegetation and palaeoclimatic changes. Floras of four subsequent stratigraphic levels show a decreasing representation of exotic elements in the Pliocene and a massive immigration of boreal elements in the Early Pleistocene. Vegetation changes start with broad-leaved deciduous and mixed mesophytic forests (BLDF, MMF) and continue to “more open” light forests of BLDF or MMF types in areas of zonal to extrazonal uplands. This vegetational change is characterised by an immigration of dry herbaceous and sclerophyllous elements. Wetland communities stepwise loose exotic components and point to cool-temperate conditions similar to the present higher in the profiles. Palaeoclimatic signals show warmer and more humid conditions for the Pliocene levels (about 15°C of mean annual temperature, 5°C of mean winter and 25°C of mean summer temperature, more than 900 mm of mean annual precipitation). Early Pleistocene proxy data indicate the beginning of a cooler phase at the Plio-Pleistocene boundary (about 7°C of mean annual temperature and decreasing trend of precipitation), but no colder conditions than the present day in the NW part of the Bohemian Massif.

Key words: flora; vegetation; palaeoclimate; Pliocene; Pleistocene; Czech Republic

1. Introduction

Plant assemblages (foliage, fruits and seeds, pollen, wood) obtained from drill cores and outcrops of the Vildštejn Formation in the Cheb Basin and the Tachov (Cheb–Domažlice) Graben in western Bohemia were assigned by Bůžek et al. (1985) to the Pliocene-Pleistocene transition, according to the stratigraphic scheme of Gibbard et al. (2010). The fossils have been known since pioneer studies by Karl Rudolph in 1935 and were more systematically evaluated by Č. Bůžek, Z. Kvaček, F. Holý, M. Konzalová, and L. Stuchlik from 1982 to 1991 (Rudolph, 1935; Bůžek et al., 1982, 1985; Stuchlik, 1982, unpublished). In the present paper the plant material described so far (Bůžek et al., 1985; Stuchlik, 1982) is re-evaluated in current taxonomical context (EM, ZK, VT) and results of subsequently analysed new pollen material (Stuchlik, unpublished) are added (AAB, LS). Several palaeoenvironmental techniques are applied on the complete fossil plant spectra from the Vildštejn Formation (Cheb Basin) and relicts of Neogene deposits of the Tachov (Cheb–Domažlice) Graben to reconstruct models of vegetation and climatic changes from the Late Pliocene to Early Pleistocene. The evaluation of the zonal vegetation at the studied sites was conducted using a semi-quantitative method of the Integrated Plant Record vegetation analysis (VT). This technique was originally designed to reconstruct the character of zonal vegetation under subtropical to temperate climate. Here for the first time, the IPR-vegetation analysis is applied on Plio-Pleistocene floras originated partly under cool-temperate conditions. The obtained results are discussed in the context of those derived from other palaeovegetational techniques allowing to reconstruct complex qualitative and quantitative characteristics of the fossil vegetation, i.e., Phytosociological approach (ZK, VT) and Plant Community Scenario approach (EV, EM). Similarly, the multi-technique approach was used to detect climatic changes during the sedimentation of the Vildštejn Formation and the Tachov (Cheb–Domažlice) Graben. The method of the Coexistence Approach (AAB) assesses palaeoclimatic estimates based on the analysis of the micro- and macrofossil plant material. The second palaeoclimatic technique is the physiognomic method of the Leaf Margin Analysis (VT). Its application is strongly limited by the scarcity of the leaf material at the studied sites. Therefore we experimentally used also elements from carpological material and estimated characters of the leaf lamina (entire vs. non-entire) based on their nearest living relatives (NLRs). The obtained climatic datasets and CA results are discussed within the frame of palaeoclimatic data obtained for other Late Pliocene and Early Pleistocene floras of Europe.

2. Geological setting

The Cheb Basin, the westernmost lignite basin within the Ohře (Eger) Graben lies on a tectonic crossing of two major structures – the Ohře (Eger) Rift of WSW-ENE direction (Ziegler, 1990) and a younger structure of the Tachov (Cheb–Domažlice) Graben trending in NNW-SSE direction (e.g., Rojík et al., 2010; Fig. 1a). Its sedimentary filling consists of several lithostratigraphic units (formations or levels), partly informally defined, deposited in the time interval from Late Eocene to Pliocene-Pleistocene (e.g., Ambrož, 1958; Václ, 1979; Bůžek, et al. 1982; Bucha et al., 1990; Špičáková et al., 2000; Kvaček and Teodoridis, 2007; Rojík et al., 2010). Besides the formally defined formations of Staré Sedlo (Late Eocene), Cypris (late Early Miocene) and Vildštejn (Plio-Pleistocene), the other lithostratigraphic units, i.e., the Lower Clay and Sand with the Lower Coal Seam and the Main Coal Seam are informally defined. Recently, Špičáková et al. (2000) described a detailed tectono-sedimentary evaluation of the Cheb Basin and the Tachov (Cheb–Domažlice) Graben focusing on three main depositional units only, i.e., the Lower Clay and Sand and Main Coal units, Cypris Formation and Vildštejn Formation. Rojík et al. (2010) and Kvaček and Teodoridis (2007) reviewed most of the so far published palaeobotanical data from the Cheb Basin with details of the geological positions. The present account will concentrate only on the youngest part of the basin fill, the Vildštejn Formation. This cycle of fluvio-lacustrine sediments was deposited after a hiatus lasting for about 12 million years partly on the Early Miocene Cypris Formation or on crystalline and granitic basement near the western border of the basin. The average thickness of the Vildštejn Formation usually varies from 30 to 60 m, but the maximal value exceeds 100 m at the Mariánské Lázně fault belonging to the tectonic system of the Tachov (Cheb–Domažlice) Graben. The Vildštejn Formation is divided into two members. The older Vonšov Member is well developed near the villages of Skalná (formerly Vildštejn or Wildstein) and Vonšov (formerly Fonsau) and represents weathered illite green clay (partly reworked Cypris claystone), grey-violet or reddish tough clay (Blauton D) and tough blue-grey pelite associated with kaolinite. Towards the East and North of the basin, sandy deposits start to occur and intermix with pelitic deposits. The younger Nová Ves Member represents a relatively heterogeneous sequence of layers with a total thickness of 20 to 50 m. The basal part is characterised by a thick layer of the dark to black clay (called Nero), which is accompanied by lignitic peat horizons in its uppermost part (Nová Ves clay pit) that form the overlying Upper Coal Seam (Václ, 1979), which typically include sandy and mica laminations. According to Bůžek et al. (1985, p. 10), the Nero Clay, generally regarded as a basal layer of the Nová Ves Member (Fig. 1), belongs rather to the sedimentary cycle of the Vonšov Member because this clay deposit is coarser, rich in mica and contains only kaolinite with less ordered structure and lower content of molecular water like clays of the Vonšov Member. Pure ball clays are whitish (except the Nero Clay) and form layers mostly in the lower part of the Nová Ves Member. The upper part is characterised by prevailing psammitic sediments. According to Bůžek et al. (1985), the uppermost part of the Nová Ves Member (Overlying sands and gravels sensu Ambrož, 1958; horizon D in this paper) surely represents an independent sedimentary cycle (Fig. 1a, b).

The Tachov (Cheb–Domažlice) Graben is partly filled by Neogene deposits which have been interpreted as fluviatile sediments of “the river F” sensu Pešek and Spudil (1986). This river system probably drained the western part of the Czech Republic towards the Cheb Basin during the Pliocene (Pešek and Spudil, 1986; Malkovský, 1995). The studied plant macro- and microfossils are known from the V1 and V2 drill cores and the Nová Hospoda clay pit (Fig. 1a). The geological section of the drill cores, as described by Nosek (1978), consists of about 10 m thick clayey sediments with thin lignitic beds and brown clays that interchange with kaolinitic clays and claystones. This fossiliferous part (mainly clayey horizons) is overlain by 5 m thick reddish weathered deposits (Bůžek et al., 1985). Pollen material was obtained from the Nová Hospoda clay pit (Gabrielová et al., 1970; Konzalová in Bůžek et al., 1985).

Exact dating of fossiliferous deposits of the Vildštejn Formation and the Tachov (Cheb–Domažlice) Graben is not always available (Fig. 1b). The palaeomagnetic records derived from the drill cores of NK-24 and NK-25 (Nový Kostel) suppose a time range from 4.7 to 1.4 Ma (Bucha et al., 1990), although these datasets must be taken just as rough estimates

(Špičáková et al., 2000, pp. 561-562; Matys-Grygar, pers. comm. 2013). Špičáková et al. (2000) present a time range from 4.5 to 1.5 Ma for the deposition of the Vildštejn Formation as a whole.

3. Material

Due to the scarcity of outcrops (mainly the Nová Ves, Vonšov and Nová Hospoda clay pits), the majority of plant material studied derives from drill cores generally situated in the NE part of the Cheb Basin (Fig. 1). The present study aims at re-evaluating all macrofossil as well as microfossil (palynological) material described by Bůžek et al. (1985). In addition, new pollen datasets from the drill core HV 2 and the Nová Ves clay pit (Fig. 2, Appendix 1) are provided. These data are the first quantitative pollen data published for this region and allow for a more detailed analysis of vegetation and climate changes.

The study follows the original concept of fossiliferous horizons within the Vildštejn Formation given by Bůžek et al. (1985) and recognizes four stratigraphic levels for quantitative analyses:

(1) Vonšov Member (Fig. 1; Table 1 – marked as B, or I.) – this level includes macrofossil floras from the drill core HV 9, and pollen data from the lower part of the Nová Ves clay pit (levels A1-A3) and the lower part of drill cores HV 2 and HV 3 (Stuchlik, 1982). Due to the sandy facies in drill cores HV 2 and HV 3 the stratigraphic boundaries between the Vonšov and Nová Ves members cannot be clearly fixed. They were characterised by Stuchlik (1982) by comparing the palynological assemblages with data from the Nová Ves clay pit. The middle parts of drill cores HV 2 and HV 3 show abundant occurrences of *Alnus* and other riparian and wetland elements (*Salix*, *Nyssa*, Cyperaceae, etc.) as well as significant occurrences of *Betula*, *Corylus*, and *Myrica*, and are comparable with part “A” (Pluto Clay) of the Nová Ves clay pit (Stuchlik, 1982). The original pollen material collected by Stuchlik from the drill core HV 2 and the Nová Ves clay pit was re-studied by us (Appendix 1). Pollen datasets from drill core HV 3 were not available. Although a clear position of the boundary between the Pluto and Nero clays is not given by Stuchlik (1982) and correlation of the pollen diagrams remains vague, we assign pollen samples from the depths of 35.3 m to 55.2 m to the Pluto Clay in the drill core HV 2 (Bůžek et al., 1985, Fig. 2) based on the above mentioned similarities in the floristic composition of the levels.

(2) Nová Ves Member (Fig. 1; Table 1 – marked as C, or II.) – this second level comprises macrofloras from drill cores HV 3, HV 4 (29.1–34.4 m), HV 6, HV 7, V 51–V 67, and pollen data from drill cores HV 2 (25.6–19.5 m) and HV 3, and the Vonšov and Nová Ves clay pits (samples B1–B4). The uppermost parts of the drill cores HV 2 and HV 3 contain pollen samples showing higher abundances of Taxodioideae/Cupressaceae, *Corylus*, Leguminosae, *Myrica*, and Rhamnaceae, and are comparable to the “level I.” of the Nero Clay sensu Stuchlik (1982), i.e., the part “B” of the Nová Ves clay pit.

(3) Nová Ves Member – lignite beds (Fig. 1; Table 1 – marked as D, or III.) –this level includes macrofloras from the upper part of the drill core HV 4 (22.8–24.3m) and the Nová Ves clay pit (layers NV 9–10) as well as pollen samples from the Nová Ves clay pit (horizons B5–B9 and C1–C7).

(4) Nová Ves Member – upper part (Fig. 1; Table 1 – marked as E, or IV.) – the macroflora from layer NV 14 and pollen samples from horizons C9, $C_{1\text{-}4}$ and D in the Nová Ves clay pit are included here.

Separately, a composite flora of the **Tachov (Cheb–Domažlice) Graben** (Fig. 1a; Table 1 – marked as A) is evaluated in this study, which consists of macrofloras from drill cores V 1 and V 2, and pollen data from the outcrop at Nová Hospoda (Konzalová in Bůžek et al. 1985).

4. Floristic analysis and phytostratigraphic correlation

The individual palaeofloristic levels within the Vildštejn Formation significantly differ in the composition and rate of geoelements (Bůžek et al. 1982, 1985; Table 1; Fig. 2; Appendix 1). The lowermost parts represent the fill of the Tachov (Cheb–Domažlice) Graben, where, besides common remains of *Glyptostrobus*, also *Corylopsis*, *Symplocos casparyi* and *Microdiptera* (incl. *Mneme*) were recorded in the macrofossil assemblage (palaeofloral assemblage A) stressing affinities with the Early Pliocene (Zanclean, 5.3–3.6 Ma) floras of the Netherland (Brunssumian – Reid and Reid, 1915; Zagwijn, 1959), the Lower Rhine Basin (Hambach 9 'Rot-Ton'– Van der Burgh and Zetter, 1998; Wetterau – Mai, 1973), Alsace (Sessenheim 'Saugbagger-Flora' – Geissert et al., 1990; Kvaček et al., 2008; Teodoridis et al., 2009), Poland (Krościenko – Szafer, 1947, Mizerna II). In Italy *Symplocos casparyi* is reported up to the Gelasian (about 2 Ma – Martinetto, 2001; Martinetto et al., 2015), and *Glyptostrobus* certainly still occurs in deposits of late Piacenzian age (ca. 2.8 Ma – Martinetto et al., 2007), and there are possible Gelasian records in central Italy (Martinetto et al., 2014) as well as a problematic wood record in the Calabrian (ca. 1.5 Ma – Ravazzi and Van der Burgh, 1994), whereas *Corylopsis* and *Microdiptera* have never been recorded there. If a correlation of the Cheb Basin to the Italian palaeofloral sequence was attempted, the assemblage A of Vildštein would certainly admit a Piacenzian age (3.6–2.6 Ma), but a Gelasian age could not be excluded. The macrofloras of the Pluto and Nero clays (the Vonšov Member and the lower part of the Nová Ves Member) are richer, including besides *Glyptostrobus* also other exotic conifers (cf. *Taxodium*, *Chamaecyparis, Pinus* cf. *spinosa, Picea* cf. *echinata*) and angiosperms (*Liriodendron, Ampelopsis*, *Acer* cf. *tricuspidatum*, *Viburnum* cf. *dilatatum*, *Weigela*, *Leucothoë narbonnensis, Epipremnites*). The common occurrence of *Quercus roburoides* and *Quercus* cf. *pseudocastanea* stresses close affinities to the Late Pliocene (Reuverian, Piacenzian) floras of Europe, e.g., Frankfurt a. M. (Germany) – Mädler (1939); Willershausen (Germany) – Straus (1992), Knobloch (1998); Berga (Germany) – Mai and Walther (1988); Auenheim (France) – Kvaček et al. (2008), Teodoridis et al. (2009); Ruszów (Poland) – Hummel (1983, 1991). Also the comparison to the Italian floras points to a Piacenzian age, because there *Taxodium*, *Weigela*, *Leucothoë* and *Epipremnites* are only reported up to the late Piacenzian (ca. 2.8 Ma – Martinetto, 1999; Martinetto et al., 2007).

According to Bůžek et al. (1985) the rate of exotic elements in the Tachov (Cheb–Domažlice) Graben and Pluto and Nero clays is 30% and 33%, respectively, whereas a transition to the higher levels of the Vildštejn Formation is indicated by a turnover of floristic characteristics. The flora of the lignite beds of the Nová Ves Member differs pronouncedly by the new immigration of elements that appear commonly in the European Pleistocene, mainly *Picea omoricoides*, *Pinus* cf. *sylvestris*, boreal Ericaceae (*Chamaedaphne*, *Oxycoccus*, *Andromeda*), and various herbs, which are typical of central to subarctic Eurasia today (*Scheuchzeria*, *Ranunculus flammula, Menyanthes* cf. *trifoliata*). The poorly documented higher levels of the mica clay from the upper part of the Nová Ves Member are dominated by the short-needle Scotch pine typical of boreal Scandinavia, with other Pinaceae, *Juniperus,* dwarf *Salix* and *Alnus.* The rate of exotic elements within the Nová Ves Member decreases to hardly 22% of the total number of taxa.

5. Methods

Five palaeoenvironmental methods have been applied in this study: Phytosociological approach, Integrated Plant Record vegetation analysis (IPR-vegetation analysis), Plant Community Scenario approach (PCS approach), Coexistence Approach (CA) and Leaf Margin Analysis (LMA). The confrontation of these methods allows in our opinion a more precise evaluation of palaeoenvironmental and palaeoclimatic aspects based on the plant fossil material studied. The method proposed by Bertini and Martinetto (2011) for the construction of palaeovegetation transects, which would have been useful to test the qualitative transects proposed for the Vildštejn palaeofloras by Bůžek et al. (1985), could not be applied because it requires several localities of the same age in different palaeogeographic contexts.

5.1 Phytosociological approach

The phytosociological approach is a widespread and the earliest vegetation reconstruction method, which is known as an intuitive qualitative approach (e.g., Heer, 1855; Saporta and Marion, 1878; Saporta, 1881; for review see Mai, 1995). Several palaeophytocenological markers are usually selected based on their abundance, and their physiognomical and taxonomical characters. On this basis the defined palaeovegetation units (including their nearest living relatives (NLRs) environmental datasets) are correlated to suitable extant vegetation units and/or subunits. Mai (1995, p. 498–603) presents most of the published vegetation types and their synonyms, thus providing a detailed overview of zonal and azonal phytosociological units in current use for the Paleogene and Neogene of Europe (Teodoridis et al. 2011a, pp. 161–162).

5.2 Integrated Plant Record vegetation analysis (IPR-vegetation analysis)

The IPR-vegetation analysis is a semi-quantitative evaluation technique developed by Kovar-Eder and Kvaček (2003) to map the integrated plant fossil records (leaf, carpological, wood, and pollen assemblages) in terms of the zonal vegetation (Kovar-Eder and Kvaček, 2007; Kovar-Eder et al., 2008). Methodologically, the IPR-vegetation analysis uses plant taxonomy, physiognomy, and autoecological characteristics to assign the studied plant record into twelve zonal (9) and azonal (3) taxonomic-physiognomic components: CONIFER (zonal and extrazonal conifers), BLD (broad-leaved deciduous woody angiosperms), BLE (broad-leaved evergreen woody angiosperms), SCL (sclerophyllous woody angiosperms), LEG (legume-like woody angiosperms), ZONPALM (zonal palms), ARBFERN (zonal arborescent ferns), DRY

HERB (open woodland and grassland elements), MESO HERB (mesophytic forest undergrowth), AZONAL WOODY (azonal woody trees and shrubs), AZNW (azonal non-woody elements) and AQUATIC (aquatic elements). A last component of PROBLEMATIC taxa includes unassigned taxa. The relative abundances of the various components of zonal woody angiosperms and zonal herb component (MESO HERB + DRY HERB) of zonal woody components are calculated as follows in Eqs 1 to 5.

Eq. 1: $\%_{\mathrm{BLD}} = BLD/(\sum(BLD,BLE,SCL,LEG,ZONPALM)) \times 100$,

Eq. 2: $\%_{\mathrm{BLE}} = BLE/(\sum(BLD,BLE,SCL,LEG,ZONPALM)) \times 100$,

Eq. 3: $\%_{\mathrm{SCL+LEG}} = SCL+LEG\ /(\sum(BLD,BLE,SCL,LEG,ZONPALM)) \times 100$,

Eq. 4: $\%_{\mathrm{CONIFER}} = CONIFER\ /(\sum(BLD,BLE,SCL,LEG,ZONPALM,CONIFER,MESO\ HERB,DRY\ HERB)) \times 100$.

Eq. 5: $\%_{\mathrm{DRY\ HERB\ +\ MESO\ HERB}} = DRY\ HERB+MESO\ HERB\ /(\sum(BLD,BLE,SCL,LEG,ZONPALM,CONIFER,MESO\ HERB,DRY\ HERB)) \times 100$.

These values (Eqs 1 to 5) have been defined as distinguishing 8 zonal vegetation types including their ecotones (Kovar-Eder and Kvaček, 2007; Teodoridis et al., 2011a): 1) temperate to warm-temperate broad-leaved deciduous forests (BLDF); 2) warm-temperate to subtropical mixed mesophytic forests (MMF); 3) subtropical broad-leaved evergreen forests (BLEF); 4) subtropical, subhumid sclerophyllous or microphyllous forests (ShSF); 5) ecotone vegetation of BLDF/MMF; 6) ecotone vegetation of BLEF/MMF; 7) xeric open woodlands (OW); and 8) xeric grasslands or steppe (= Xeric grassland). Thresholds for vegetation types 1 to 4 were validated on living assemblages from China and Japan considering also the definition of the transitional vegetation (Teodoridis et al., 2011b). A new IPR-vegetation database was built to organise and summarise the existing fossil and modern results (Teodoridis et al., 2011a; for details see www.iprdatabase.eu). Recently, Teodoridis et al. (2012) also tested the IPR vegetation analysis on Palaeogene European floras and modern tropical vegetation from China.

Due to the low diversity especially of zonal woody angiosperms in the studied material from the Vildštejn Formation and the Tachov (Cheb–Domažlice) Graben, the IPR vegetation analysis is not reliably applicable to many of the assemblages (for less than 12 zonal woody angiosperm taxa – see Table 2). However, the values of coniferous and herbaceous components (CONIFER, DRY HERB, MESO HERB) are still informative in these cases, because they are calculated based on the sum of all zonal taxa (see Eqs 4, 5).

5.3 Plant Community Scenario approach (PCS approach)

Leaf, carpological and pollen datasets of the Vildštejn Formation and the Tachov (Cheb–Domažlice) Graben are re-evaluated also by means of a recently proposed standardised approach for quantitative plant assemblage analysis and graphical rendering of floral-palaeofloral data: the “Plant Community Scenario” (PCS) approach (Martinetto and Vassio, 2010; Vassio and Martinetto, 2012). The PCS approach is based on the standardised quantitative analysis of plant assemblages in a given volume of sediment. The quantitative data concerning a sigle category of plant parts (e.g. carpological remains, leaves, pollen and spores) and some related qualitative attributes are then converted and illustrated in a simplified 2D sketch (PCS) which has a similar appearance as a vegetation transect. Qualitative information provided for each taxon is synthesised into the PCS by means of “growth forms” (plant categories, Appendix 2) and by subdividing the profile of the PCS transect into different ecological subzones (dry, mesophytic, hygrophilous, aquatic) to better display the ecological preferences of the dominant taxa. The resulting vegetation transect conventionally comprises 50 “plant symbols” proportional to the relative abundance of each plant category in the studied assemblage. The analysis of plant assemblages by means of the PCS approach and the visualisation of vegetation sketches allow the standardised, homogeneous and easy comparison within palaeobotanical datasets (Figs 3, 4 and 5). The PCS approach, so far restricted mainly to carpological assemblages (Martinetto and Vassio, 2010; Vassio, 2012; Vassio and Martinetto, 2012), can also be applied to pollen (Martinetto et al., 2012; Vassio, 2012) and leaf assemblages (Vassio, 2012). Yet, initial results in using the PCS representation for palaeovegetation reconstruction have been obtained only for fruit and seed assemblages based on the combined study of modern standing vegetation (directly surveyed) in a limited catchment area and the modern carpological assemblages buried by its drainage system (Vassio, 2012; Vassio and Martinetto, 2012; Fig. 6). The aim of this research was to describe the quantitative taphonomical bias between the real standing vegetation and the final composition of the carpological assemblages originated from it. The gathered data were used to produce coupled vegetation survey-PCS and deposit-PCS, whose comparison is the key for a better interpretation of a deposit-PCS in a fossil context, in which the corresponding palaeovegetation represents the unknown variable (Vassio, 2012; Vassio and Martinetto, 2012). The pictures of the vegetation provided by modern deposit–PCSs can be assumed as models to be compared with ancient deposit–PCS in order to find the best modern deposit analogues. Then, the coupled information of modern deposit–PCS plus modern vegetation-PCS can be used as a key for the interpretation of the PCSs obtained from fossil assemblages. At present, the number and the environmental coverage of modern deposit-PCSs is still not sufficient to always enable the determination of modern models of vegetation for fossil assemblages (Bertolotto et al., 2012; Vassio, 2012; Vassio and Martinetto, 2012).

In the present paper, the first experiment of applying the quantitative PCS approach to three plant part records (carpological remains, leaves, pollen and spores) collected from the same sedimentary layers aims at pointing out, discussing and comparing different information, i.e., the represented source area, a possible taphonomical bias, and peculiarities provided by each palaeobotanical dataset.

5.4 Coexistence Approach (CA)

The five flora lists of the different stratigraphic levels described above and given in Table 1 have been assigned to quantitative climatic analyses with the Coexistence Approach (CA, Mosbrugger and Utescher, 1997; Utescher et al., 2014) for micro- and macrofloras separately to compare local and regional climate signals. Due to the general agreements of both signals, micro and macro data also have been combined to provide a higher resolution of results. Additionally, the CA has been applied to all single pollen floras of the drill core HV

2 and Nová Ves clay pit separately (Appendix 1) to assess the climate variability within the studied stratigraphic interval of the Vildštejn Formation. Seven climate parameters have been calculated by the CA: MAT (mean annual temperature), CMMT (mean temperature of the coldest month), WMMT (mean temperature of the warmest month), MAP (mean annual precipitation), as well as HMP (precipitation of the wettest month), LMP (precipitation of the driest month), and WMP (precipitation of the warmest month). Based on the assumption that the climatic requirements of Neogene plant taxa are similar to those of their nearest living relatives (NLRs), the aim of the CA is to find the climatic ranges in which a maximum number of NLRs of a given fossil flora can coexist. Those coexistence intervals (one for each climate parameter) are considered the best description of the palaeoclimatic situation under which the given fossil flora lived (for a detailed discussion and introduction to the method see Mosbrugger and Utescher, 1997 and Utescher et al., 2000, 2014). The application of the CA is facilitated by the computer program ClimStat and the database PALAEOFLORA which contains NLRs of more than 7500 Cenozoic plant taxa, together with their climatic requirements (1730 datasets) which are derived from meteorological stations located within the distribution areas of the taxa (for details see www.palaeoflora.de). The resolution of the calculated climate data varies with respect to the parameter examined; it is highest for temperature-related parameters where it is usually in the range of 1 to 2 °C; results for mean annual precipitation reach an accuracy of 100 to 200 mm (Mosbrugger and Utescher, 1997). Typically, the resolution and the reliability of the resulting coexistence intervals increase with the number of taxa included in the analysis, and are relatively high in floras with ten or more taxa for which climate parameters are known.

Some authors doubt the reliability of the Coexistence Approach especially for certain environmental conditions like mountainous regions (e.g., Kvaček, 2007; Grimm and Denk, 2012). However, methodological proxy-proxy and model-proxy comparisons as well as several applications of the CA on Oligocene to Pliocene European floras showed its reliability and good climatic resolution (e.g., Bruch et al., 2007, 2011; Utescher et al., 2011, 2014). Utescher et al. (2014) discuss these controversies and give a detailed overview of the power and limitations of the Coexistence Approach. To get additional independent climate data for comparison and validation, Leaf Margin Analysis (LMA) has been conducted to the material as well.

5.5 Leaf Margin Analysis (LMA)

Leaf margin analysis is a univariate leaf physiognomic technique based on the empirical positive correlation between mean annual temperature (MAT) and the proportions of taxa with toothed vs. taxa with entire leaf margins (woody dicots) of non-pioneer vegetation (Bailey and Sinnott, 1916). Wolfe (1979) devised this method and compiled 34 humid to mesic floras from East Asia, including the reference datasets of Wang (1961), to build a linear regression equation to predict temperature – see Eq. 6. Recently, Su et al. (2010) re-evaluated original Wolfe's datasets and introduced a new equation (Eq. 7) from humid to mesic forests from China. Traiser et al. (2005) present regression equation (Eq. 8), which is based on European datasets containing 1835 reference sites. Sampling errors (SE1) and (SE2) were calculated by Wilf (1997) and Miller et al. (2006) – see Eq. 9 and Eq. 10. For the assemblages from Vildštejn Formation and the Tachov (Cheb–Domažlice) Graben, the application of LMA is strongly limited by a low abundance of leaf material in the studied floras. We therefore experimentally used elements typified by pollen and carpological remains. In such cases, the tooth and/or entire character of the leaf lamina is estimated based on the known characters of their nearest living relatives (NLRs) presented in Table 1. This indirect determination of leaf characters should influence the accuracy of the results further than estimated in Eq. 9 and 10.

Eq. 6: $\mathrm{MAT}_{\mathrm{LMA}\ 1} = 30.6 \times P + 1.41$; ($r^2 = 0.98$),

Eq. 7: $\mathrm{MAT}_{\mathrm{LMA}\ 2} = 27.6 \times P + 1.038$; ($r^2 = 0.79$),

Eq. 8: $\mathrm{MAT}_{\mathrm{LMA}\ 3} = 31.4 \times P + 0.512$; ($r^2 = 0.60$),

where r^2 (coefficient of determination).

Eq. 9: $\mathrm{SE}\ 1_{\mathrm{MAT}} = c\,\sqrt{([(P(1-P))/n)]}$,

where c (slope of the MAT vs. leaf margin regression, equals 30.6 here), n (total species number), P (proportion of *n* species with entire margin, $0 < P < 1$).

Eq. 10: $\mathrm{SE}\ 2_{\mathrm{MAT}} = \sqrt{([1 + \varphi\ (n-1)\ P(1-P)] \times (P(1-P))/n)}$,

where $\phi = 0.052$ (dispersion factor), P ($0 < P < 1$) is the percentage of woody dicots with entire leaves; and n is the total number of woody dicots.

To compare results of LMA derived from the above presented equations (Eqs 6 to 8), a value of mean absolute deviation (MAD) was calculated as follows (Eq. 11):

Eq. 11: $MAD=1/n \sum^{n}_{(i=1)} |x_i-\bar{x})|$,

where x_i (data element), $\bar{x}$ (mean of the dataset).

6. Palaeoenvironmental reconstruction

The three palaeovegetational techniques (Phytosociological approach, IPR-vegetation analysis and PCS approach) and two palaeoclimatic methods (LMA and CA) have been applied on the studied plant assemblages from the Vildštejn Formation and the Tachov (Cheb–Domažlice) Graben to re-evaluate and quantify the previous vegetation and climatic characteristics presented by Bůžek et al. (1985) and to allow to discuss these data in the light of the newly applied techniques.

6.1 Vegetation reconstruction

6.1.1 Phytosociological approach

The older part of the Vildštejn Formation, the Vonšov Member – Pluto Clay (Bůžek et al., 1985, Fig. 4.1), is characterised by an assemblage indicating a mixed coniferous and broad-leaved deciduous forest growing on mesic habitats (e.g., *Pinus*, *Picea*, *Larix*, *Liriodendron*, *Quercus*, *Castanea*, *Taxus, Ilex*). However, the three latter elements documented in the carpological record are usually interpreted as wetland plants (e.g., Mai and Walther, 1988). This forest probably overlapped with riparian vegetation and swamps dominated by shrubs and herb undergrowth (e.g., *Taxodium, Acer, Chamaecyparis, Ranunculus, Ampelopsis, Rubus, Nuphar, Polygonum, Sparganium, Dulichium, Carex, Potentilla, Potamogeton*, *Najas*). The studied pollen spectra of the Pluto Clay of the Vonšov Member, i.e., horizons A 1-3 of the Nová Ves clay pit and the middle part of the drill cores HV 2 and HV 3 sensu Stuchlik (1982), generally prove the mixed coniferous and broad-leaved deciduous forest vegetation type and show a predominance of swamp and riparian elements, such as Polypodiaceae, *Myrica*, *Salix*, *Alnus*, and mesophytic elements, e.g., *Betula*, *Carpinus*, *Corylus*, *Engelhardia*, *Symplocos*, *Juniperus*, *Keteleeria*, *Cryptomeria*-type, *Abies* (see Table 1, Fig. 2). Bůžek et al. (1985, p. 49) pointed out similar modern vegetation types from the USA and southern Europe. In the USA, the area of Weymounth Pine mixed forests approaches the *Taxodium* alluvial forests (with *Nyssa*, *Acer rubrum*, various deciduous oaks) and the *Chamaecyparis* swamp forests. Wet areas outside forests are covered there with sedges, which include also *Dulichium* (Knapp, 1965). Similarly, broad-leaved deciduous forests are known from wet soils biotopes of the sub-Mediterranean zone in Europe, characterised by *Querco-Carpinetum betuli* association, while *Pinus peuce* builds poor stands occupying higher mountain biotopes over 1.500 m alt. (Horvat et al., 1974).

The reconstructed vegetation based on the studied plant fossils from the Tachov (Cheb–Domažlice) Graben shows close affinity to those reconstructed above for the Pluto Clay.

The studied assemblages of the Nero Clay in the Nová Ves Member show a very similar vegetation pattern corresponding to those of the Vonšov Member (see Bůžek et al., 1985, Fig. 4.2). The macrofossil plant material indicates a change in floristic compositions, e.g., the absence of *Quercus, Castanea, Liriodendron, Larix, Picea* contrary to new occurrences of

Pinus cf. *spinosa*, *Corylus*, and new aquatic elements, such as *Proserpinaca*, *Nymphaea*, *Najas*, *Menyanthes*, *Juncus*, *Cyperus*, *Cladium*, *Caldesia*, while the pollen spectra show almost identical taxa composition with higher abundances of Taxodioideae/Cupressaceae, *Corylus*, Leguminosae, *Myrica*, and Rhamnaceae (see Table 1). A high frequency of the mentioned aquatic and marsh elements corresponds to fluvial to oxbow lake or periphery of basin environments within the zonal broad-leaved deciduous forest on their upland periphery.

The vegetation reconstructions of the next stratigraphic level of the Nová Ves Member (lignite beds) studied here are based on the floras of the Nová Ves pit (NV 9–10) and drill core HV 4, characterised by Bůžek et al. (1985, Fig. 4.3) as mesotrophic transitional moor with Cyperaceae, *Scheuchzeria*, *Menyanthes* associated with *Pinus* cf. *spinosa*, overlapped in oligotrophic areas to vegetation dominated by Ericaceae (*Andromeda polifolia*, *Chamaedaphne calyculata, Oxycoccus*) and in alluvial parts to forest vegetation characterised by *Picea omoricoides* and *Chamaecyparis* cf. *pisifera*. Bůžek et al. (1985) noted analogous modern vegetation in the cool temperate zones of the northern Atlantic part of the USA, like the Northern broad-leaved and Weymounth Pine forest sensu Knapp, (1965, p. 85), and Europe; the wet rock habitats with *Picea omorika* in the Drina valley at 800-1000 m alt. (Horvat et al., 1974), or the lowland peat bogs with *Chamaedaphne calyculata* in Finland (Overbeck, 1975). Besides an increase in the abundance of *Pinus sylvestris* type, the pollen spectra of the Nová Ves pit show a strong decrease in diversity. Abundances of herbaceous and aquatic plants increase and arboreal riparian elements decrease (*Alnus, Salix*) indicating a change especially in the azonal vegetation. The stratigraphically youngest plant fossils from the Nová Ves clay pit (NV 14, C9, C_{1-4}, D) indicate a spreading of the coniferous forest vegetation type dominated by pines (*Pinus* cf. *halepensis*, *Pinus* cf. *sylvestris*) in the association with *Picea omoricoides*, *Abies* sp., and *Juniperus* cf. *communis*. The coniferous forest probably overlapped with riparian vegetation with *Alnus* cf. *rugosa* and *Salix* and moor and aquatic vegetation with *Menyanthes* cf. *trifoliata*, *Elatine alsinastrum*, *Andromeda polifolia*, *Artemisia*, Cyperaceae etc. (Břžek et al., 1985, Fig. 4.4; Table 1). These vegetation types are comparable to modern vegetation known from the Taiga zone (Bůžek et al., 1985).

6.1.2 IPR-vegetation analysis results

According to the thresholds of key components for vegetation types (see the Eqs 1–5) re-established by Teodoridis et al. (2011b), possible zonal vegetation assemblages are classified (see Table 2). The number of elements per fossil flora varies from 42 to 126, and Appendix 3 shows how each element is scored for each stratigraphic level in this study. The results derived from the Vonšov Member (Pluto Clay) show a relatively high abundance of arboreal elements, i.e., BLD component (78 and 81%), BLE component (17 and 15%), and conifers (16 to 21 %), associated with slightly lowervalues for zonal herbs varying from 32 and 33%. Such compositions of the key components correspond more or less to transitional vegetation of BLDF/MMF and BLDF vegetation types (see Teodoridis et al., 2011a, Table 2). The values of the zonal herb component exceed 30 % (the threshold for the BLDF and BLDF/MMF vegetation types according to Teodoridis et al., 2011a). Stratigraphically comparable floras from the Tachov (Cheb–Domažlice) Graben show similar results, where the values of the coniferous, BLD, BLE and zonal herb components vary from 14 to 28 %, 83 to 87 %, 15 to 10 %, and 33 to 27 %, respectively, based on the studied macrofossil and microfossil plant remnants. The characteristics of zonal elements show a close relation to the BLDF vegetation type, however, in the analysis of fossil pollen one of the values for the zonal herb component is higher.

The results of the IPR vegetation analysis calculated for the floras of the Nová Ves Member (Nero Clay) show a distinct increase in the abundances of SCL + LEG component (8%) and zonal herbs (35 to 39 %), but values for coniferous, BLD and BLE components are almost identical with those from the older levels of the Vildštejn Formation and the Tachov (Cheb–Domažlice) Graben. This specific composition can be described in two ways, as BLDF and/or transitional vegetation of BLDF/MMF vegetation types.

The next two stratigraphic levels of the Nová Ves Member, the lignite beds and the upper part, are characterised by a distinct increase in the relative abundance of the zonal herb component, generally exceeding 40 % (max. 50 %, Table 2). These herbaceous elements are associated with taxa of the SCL + LEG component, which are represented in relatively high numbers varying from 7 to 11 %, and with BLD and BLE elements in slightly lower quantities (73 to 83 % and 7 to 11 %). Abundances of the coniferous component vary from 16 to 39 % of the zonal elements. The assignment of the studied floras from lignite beds of the Nová Ves Member to vegetation types is equivocal and may correspond to three possible types that are Xeric grasslands or steppe, transitional vegetation of BLDF/MMF and/or vegetation of MMF. The studied floras from the upper part of the Nová Ves Member were excluded from the analysis due to the low number of zonal angiosperms elements (Table 2).

Generally, the results of the IPR vegetation analysis indicate several important trends of vegetation changes during the Late Pliocene to Early Pleistocene period (Table 2, Fig. 7): a) increase of the DRY herb component within the general increase of zonal herbaceous elements, b) increase of the SCL + LEG component, and c) decrease of the BLE component.

6.1.3 PCS approach results

Taxa lists provided by different palaeobotanical records (pollen, leaf and carpological, see Appendix 4) show numerous discrepancies in terms of taxonomical resolution, taxa richness, and quantitative representation of the same taxon. Almost all pollen taxa have been determined at genus or family level, whilst leaf and carpological taxa provide a more detailed taxonomical identification (most of them are listed at species or genus level). The pollen record has been described as constituted by 100 taxa belonging to 61 families (ferns excluded; 35 taxa at genus level); the leaf record consists of 23 taxa attributed to 9 families (ferns excluded); within the seed and fruit record 65 taxa and 37 families have been described.

The application of the PCS approach to the fossil assemblages of the Vildštejn Formation and the Tachov (Cheb–Domažlice) Graben provided separate graphical sketches for each of the three studied plant organs (pollen, leaves, fruits and seeds), as shown in Fig. 3 for the assemblages of the Nová Ves Member (Nero Clay, assemblage B). The discrepancies between these three PCSs show very well how differently the signal of ancient vegetation is recorded by different types of plant parts.

The pollen and leaf PCSs (Figs 3 and 5) are very similar within all the layers analysed and depict a mesic forest variously dominated by conifers. The pollen records also yield some information from the wetland areas, which is not recorded in the leaf flora at all but seems to be predominantly represented by the fruit and seed record (Figs 3 and 4). Most probably none of these different records provides an accurate picture of the palaeovegetation, but the integration of information from the three sources (pollen, leaves and fruits/seeds) can lead us to a more sound interpretation with respect to the qualitative reconstructions by Bůžek et al. (1985). However, only for the fruit and seed record modern datasets are available permitting a comparison and interpretation of PCSs in terms of palaeovegetation. The four graphical sketches based on carpological data (Figs 3and 4) show a very poor arboreal cover. Most of the transect is occupied by herbaceous freshwater macrophytes and hygrophilous plants, which have been found to be overrepresented in analogous modern situations (Vassio, 2012). Probably the sedimentological setting of the Vildštejn Formation did not allow a broad-scale representation of vegetation in the fruit and seed assemblages (Appendix 4) due to the lack of concentrated carpodeposits (sensu Gee et al., 2005). The absence of carpological remains of some taxa occurring in the leaf record (*Castanea*, *Acer*, Pinaceae, *Quercus* and other Fagaceae) can be explained by the large dimensions of their diaspores and partly by the sampling techniques (the possibility to detect a large sized seed or fruit is limited in core samples). Moreover, if these plants grew in environments which were not in the direct vicinity of the sedimentary basin, the rather large size of their fruits/seeds would have hampered the transport to the deposition site because of the probable absence of strong currents.

The Vildštejn fruit and seed-PCSs have been compared to all of the modern carpological deposit-PCSs so-far obtained by analysing different types of modern vegetation and environmental situations in Northern Italy (Vassio, 2012; Vassio and Martinetto, 2012), in order to interpret the original source vegetation context. The PCS with the most similar structure to the Vildštejn PCSs was provided by a modern fruit and seed assemblage of the locality named “Orco 1” (small oxbow lake along the Orco river, San Benigno Canavese, NW Italy, 15 km apart from the Alps fringe; Fig. 6). The Orco 1 deposit-PCS (Fig. 6.3) derives from the study of a carpological assemblage formed in a small pond (20 m in diameter), which was associated to a scarcely extended wetland area, largely surrounded by mesic woodland vegetation (Figs 6.1 and 6.2). The similarity of the Orco 1 deposit-PCS to the Vildštejn PCSs (Figs 3 and 4) implies that the Vildštejn fossil assemblages could have been formed in a vegetation context similar to Orco 1. However, this is only one possibility, because it can be assumed that an “Orco 1-type” of PCS may as well occur in a different context, for example a wide wetland with far-growing mesic vegetation (no modern PCSs are presently available for this situation). In addition, several modern studies of seed and fruit assemblages in lakes and mires (e.g., Birks, 1973; Collinson, 1983; Dieffenbacher-Krall and Halteman, 2000) agreed in indicating the generalised occurrence of a very local vegetation record, with a poor to absent documentation of the regional vegetation. Thus, the PCS analysis of the Vildštejn carpofloras would suggest a detailed but very local picture of the fossil flora and vegetation.

The pollen PCSs (Figs 3 and 5) show in all cases more diversified transects with a dominant and varied woody component. It should be emphasised that these PCSs are based on the same qualitative and quantitative data which are commonly used for the interpretation of palaeovegetation on the basis of pollen diagrams, and partly for this reason they show several similarities to the qualitative reconstructions given by Bůžek et al. (1985).

6.2 Palaeoclimatic signals

6.2.1 Coexistence Approach (CA) results

Results of the Coexistence Approach (CA) analysis of macro and micro floral assemblages for the studied stratigraphic levels give narrow coexistence intervals for samples from the Vonšov Member (Figs 8 and 9; Tables 3 and 4). Results from the upper part of the Nová Ves Member are clearly less precise due to the lower number of taxa considered especially for data based on pollen. Generally, results from samples of pollen and macro flora are in very good agreement and CA analysis of single pollen samples from the Pluto Clay (the Vonšov Member) and the Nero Clay (the Nová Ves Member) of the drill core HV 2 and Nová Ves clay pit have provided very similar numerical results (Tables 3 and 4). The fact that they show no obvious temporal change documents relatively stable palaeoclimatic conditions during the time of the Vonšov and the early Nová Ves Member depositional setting.

The quantitative results show temperature values considerably higher than present for Tachov (Cheb–Domažlice) Graben, Pluto Clay (Vonšov Member) and Nero Clay (the lower part of Nová Ves Member) with mean annual temperatures (MAT) of about 15 °C, winter temperatures (CMMT) around 5 °C and summer temperatures (WMMT) of about 25 °C (Fig. 8, Tables 3 and 4). In fact, these values are very similar to the ones obtained from the Early Miocene Cypris Formation (Table 4). However, samples from higher levels of Nová Ves

Member (lignite beds and upper part) provide data that are close to the present day situation with MAT of 7 °C and CMMT of about -3 °C. Only summer temperatures (WMMT) remain higher than the present day value of 16 °C (meteorological station of Cheb, Table 3, Fig. 8). Moreover, results of this parameter consist of two coexistence intervals which indicate either a transitional phase of climate change with vegetation units that are not in equilibrium or represent a mixture of climate signals. The latter could be explained either by a mixture of plant fossils originating from different contemporary vegetation zones or by a mixture of fossils from subsequent climatic settings. The latter, a mixture of different climatic signals, appears to be more likely at the beginning of the Pleistocene with its increasing climate cyclicity. Here, only high-resolution sampling and clear stratigraphic control may be able to give data of higher precision.

Similar to temperature parameters, the precipitation values show annual precipitation higher than present in the older parts of the Cheb Basin (the Tachov /Cheb–Domažlice/Graben, Pluto and Nero clays) with 800–1000 mm, and close to the present day values in the upper part of the Nová Ves Member (lignite beds and upper part) with 641–766 mm and 422–766 mm, respectively (Fig. 9, Table 3). Also precipitations of the wettest month (HMP) and of the warmest month (WMP) decrease in time, whereas the precipitation of the driest month (LMP) does not reflect significant changes. In general, precipitation data from the Cheb Basin show a development towards modern conditions.

6.2.2 Leaf Margin Analysis (LMA) results

Proxy data derived from LMA based on the studied floras/stratigraphic levels of the Vildštejn Formation and the Tachov (Cheb–Domažlice) Graben are given in Table 5. The obtained estimates for MAT show generally balanced values for the studied floras, which are independent of the used regression equations, coefficient of determination (r^2) and/or modern calibration datasets (Europe vs. SE Asia), see Eqs 6 to 8. This fact is proved by low values of MAD not exceeding 0.5 °C. With regard to the stratigraphic context, no significant trend is becoming evident during the Vildštejn Formation setting (from Pluto Clay to the mica sandy deposit of Nová Ves). Generally, the LMA data vary from 7.5 to 11.6 °C and show significantly lower values of MAT than those from CA (see Tables 3, 5 and 6). Only the MAT estimated for the upper part of the Nová Ves Member shows a comparable value to the CA data.

7. Discussion

7.1 Vegetation cover

The plant spectrum of the Vonšov Member (Pluto Clay) shows relatively high abundances of the broad-leaved deciduous (BLD) component compared to relatively low amounts of the sclerophyllous (SCL+LEG) component. The general character of the zonal vegetation type should be interpreted as an ecotonal vegetation of mixed mesophytic forest and broad-leaved deciduous forest (MMF/BLDF) and/or a BLDF vegetation type for the basal Pluto Clay and for the Tachov (Cheb–Domažlice) Graben. The results are strongly affected by low numbers of zonal woody angiosperms (i.e., 6 and 9, Table 2), which limit the reliability of the method. However, the values for the conifer and herbaceous components are accepted in these cases, because their calculation is based on the total number of zonal elements (only results derived from the macrofossil plant material of the Tachov (Cheb–Domažlice) Graben and the Nová Ves Member had to be excluded). The relatively high abundances of zonal herbs (over 30%) make a linking to an appropriate zonal vegetation type very problematic. Kovar-Eder et al. (2008, Table 4) defined this threshold for the BLDF type as mostly ≤ 30%. Yet, studied living vegetation assemblages of BLDF and MMF from Japan and China show distinctly higher values of this component exceeding 30 %, e.g., assemblages of the BLDF from Shirakami Sanchi (Japan) contain 39, 47 and 53 % of zonal herbs; those from the Meili Snow Mts. (China) comprise 63 and 58 % (Teodoridis et al., 2011b, Table 7). According to the results of the IPR vegetation analyses on modern vegetation from China and Japan, Teodoridis et al. (2011b) reveal a distinct underrepresentation of zonal herbs in the fossil record, regardless of whether dealing with leaf, pollen, or fruit assemblages. This fact can be applied on the studied floras of the Vonšov Member (Pluto Clay), the Tachov (Cheb–Domažlice) Graben as well as on the floras of the Nová Ves Member (Nero Clay), see Table 2. Therefore the unequivocal results of the IPR vegetation analysis and the classifications to BLDF and BLDF/MMF types can be accepted. These predicted vegetation types for the Vonšov Member (Pluto Clay) and the Tachov (Cheb–Domažlice) Graben correspond to the syntaxomomical results previously published by Bůžek et al. (1985) as vegetation types of mesic mixed coniferous and broad-leaved deciduous forest (see chapter 6.1.1). The value of zonal conifers detected by the IPR vegetation analysis (15 to 28 %) proved the important role of the coniferous elements within the BLDF and/or transitional vegetation of BLDF/MMF.

Generally, the IPR-vegetation analysis results of the Nová Ves Member (Nero Clay and lignite beds) show a significant increase of abundance of the SCL + LEG component in account of the BLD component. Besides, the high number of dry herbaceous elements from this stratigraphic level can evocate changes in the composition and structure of the vegetation cover. This change can be interpreted as a transition from dense canopy vegetation of BLDF or BLDF/MMF to “more open” light forests of the BLDF or MMF types in areas of zonal to extrazonal uplands. The high abundance of herbaceous component exceeding 44 % indicates a close relation to the vegetation type of Xeric grasslands or steppe (Kovar-Eder et al. 2008, Table 4). Kovar-Eder et al. (2008) distinguished this vegetation type by three late Miocene floras from Russia (Sal-Manytsh watershed, drill cores near Sinjavka and Puchljakovskij farmstead). However, only the pollen flora of Puchljakovskij farmstead shows a similar composition of the other key components to the floras of the Nová Ves Member (Puchljakovskij farmstead: BLD 77 %, BLE 7 %, SCL+LEG 16 %, DRY HERB 24 % and MESO HERB 19 %). It is evident that Xeric grasslands or steppe show higher values of DRY HERB elements than our results from the Nová Ves Member, therefore this type of vegetation can be excluded as a zonal model of vegetation for our studied assemblages. This fact is supported also by a high proportion of arboreal pollen in the Nová Ves Member (Fig. 2), as well as the above mentioned high proportion of the BLD component (73 to 83 %, Table 2, Fig. 7). Similarly, the qualitative analysis carried out by Bůžek et al. (1985) considered the mixed coniferous and broad-leaved deciduous forest type for the Nová Ves Member having been replaced by coniferous forest (*Pinus*, *Picea*, *Juniperus*, *Abies*) during the sedimentation of the upper part of the Nová Ves Member setting. Relevant azonal vegetation types show a wetland to lowland swamp character dominated by shrub and herbaceous elements of Ericaceae, Cyperaceae, and Poaceae that is passing into moor and aquatic environments. Those are well depicted by PCS results based on carpological datasets, preferentially recording such environments. In summary, the balanced values of CONIFER, BLD, BLE components and the increase of zonal herbs can corroborate the existence of zonal forest vegetation throughout the Vildštejn Formation setting. The distinct increase of abundances of SCL + LEG and DRY HERB components from 4.5 to 10.6 % and 11 to 17 % (average values) within the Vildštejn Formation should evocate a structural change from dense vegetation to more open light forests rather than the transition to a steppe environment. This interpretation is supported also by the palaeoclimatic data which records a temperature change from clearly above to close to modern values (Fig. 8, Table 3) excluding harsh climatic conditions and a consequential vegetation collapse caused by glacial events.

The IPR vegetation analysis has not been widely applied to Pliocene floras yet. Besides the study of Kovar-Eder et al. (2006, 2008) of slightly older, i.e., latest Miocene, plant assemblages from Southern Europe, only Teodoridis et al. (2009) published results from the Auenheim-Sessenheim floristic complex covering a similar stratigraphic age as the floras from the Cheb Basin. The carpological flora of Sessenheim ”Saugbagger-Flora” and the composite flora of Auenheim (based on leaves and carpology) provide abundances of the key components of BLD, BLE, SCL+LEG and zonal herb components of 76.4 %, 20.3 %, 3.3 % and 13.5 %, which indicate the MMF vegetation type for Sessenheim (Teodoridis et al., 2009). Following the updated classification of IPR vegetation analysis sensu Teodoridis et al. (2011a) such values correspond to ecotone vegetation of BLDF/MMF. The younger flora of

Auenheim is characterised by a predominance of BLD components (89 %) contrary to rare evidence of BLE, SCL+LEG, and zonal herb (4%, 7 %, and 1.6 %), which fits to the BLDF vegetation type. On the other hand, a relatively higher percentage of zonal conifers (16.39 % of zonal elements) represented by mainly boreal elements, such as *Picea* and *Abies* (typical of the mixed coniferous and broad-leaved deciduous forests) can be interpreted as a characteristic feature of most Late Pliocene floras of Europe (Teodoridis et al., 2009) and floristically corresponds to the studied floras of the Nová Ves Member (lignite beds and upper part – see chapter 6.1.1, Bůžek et al., 1985).

The PCSs (Figs 3, 4 and 5) do not show the structure of ecotonal vegetation of mixed mesophytic forest and broad-leaved deciduous forest (BLDF/MMF) because the PCSs do not represent actual reconstructions of the zonal ???? palaeovegetation, in contrast to the IPR-vegetation analysis. Only the pollen PCSs could better represent the original palaeovegetation structure (Figs 3 and 5), but even in this case the well-known overrepresentation of saccate pollen (as well as other biases) provides an inconsistent shift in the appearance of the transect towards a conifer dominated woodland. The fruit and seed PCSs, based on the Orco 1 modern analogue (Fig. 6), seem to reflect rather accurately the wetland and aquatic plant communities. Those appear to be very similar to the modern ones of central Europe, yet with the occurrence of a few exotic plants (*Decodon, Dulichium, Proserpinaca*) at least in the assemblages presented on Fig. 6. Conversely, in the youngest vegetation assemblage of the Nová Ves Member – upper part (Nová Ves pit NV 14 – Fig. 5D) such exotic elements play no role in the vegetation, whereas the appearance of *Scheuchzeria palustris*, in association with *Carex nigra*, points to the establishment of a cold-temperate (or boreal if you prefer- it's the same) peat bog community (*Scheuchzerio-Caricetea fuscae*) in the basin.

7.2 Climate signals

The climatic datasets derived by the CA analysis of the Cheb Basin floras document a general decrease of temperature and precipitation parameters from the older floras of Tachov (Cheb–Domažlice) Graben, Vonšov Member (Pluto Clay), and the lower part of Nová Ves Member (Nero Clay) towards the younger floras from the upper part of the Nová Ves Member (lignite beds and upper part). However, LMA datasets are close to the modern MAT value and do not show such a cooling trend but relatively stable climatic conditions with values lower than the CA results for the oldest studied floras and higher than those of CA for the youngest floras (Nová Ves Member – upper part). This discrepancy in the results of both methods is due to the relatively low number of entire margined taxa (23 to 33%) and could be caused by the nonstandard application of the LMA technique (using non-leaf material). However, the low abundances of entire elements may be also influenced by others than climatic factors. Elements with dentate leaves frequently occupy riparian vegetation units (wetlands in general) rather than mesophytic zonal uplands plant assemblages and therefore can lead to colder estimates for riparian vegetation assemblages by physiognomic techniques (LMA and Climate Leaf Analysis Multivariate Program – CLAMP) contrary to Nearest Living Relative approaches (e.g., Teodoridis, 2004). In fact, this seems to be the case for the lower LMA temperatures of the Vildštejn Formation and the Tachov (Cheb–Domažlice) Graben compared to CA results.

Few Plio/Pleistocene palaeobotanical sites are reported from Central Europe which were studied for climatic quantifications and could serve for comparison (see Fig. 10). Some of those floras have very poor age control and are assigned to Early or Late Pliocene by floristic comparison, although some lack even such information, e.g. the Frankfurt 'Klärbeckenflora' (Mädler, 1939; Krutzsch, 1988). Based on CA analysis Uhl et al. (2007) give MAT data of 14.4 to 15.5 °C for this flora. Floras dated to Early Pliocene (with radiometric ages from 4.55 to 4.2 Ma) are Gérce and Pula in Hungary. Those were analysed by Erdei et al. (2007) with values for Gérce of 15.6–15.7 °C (MAT), 5.0–5.0 °C (CMMT), 24.7–24.8 °C (WMMT), 843–1160 mm (MAP) and for Pula of 10.0–15.7 °C (MAT), 0.2–4.8 °C (CMMT), 24.7–24.8 °C (WMMT), 619–1160 mm (MAP). Uhl et al. (2007) published MAT data derived by various methods for the floras of Berga/Turingia and Willershausen. Mai and Walther (1988) as well as Krutzsch (1988) correlated both floras with the Reuverian (Piacenzian, Late Pliocene). Climate values for Berga/Turingia based on CA range from 13.3 to 16.6 °C (MAT), and from 12.5 to 16.5 °C for the locality Willershausen. All those values are very similar to the results of the studied floras from the Tachov (Cheb–Domažlice) Graben, Vonšov Member and the lower parts of the Nová Ves Member confirming climatic conditions during the Pliocene of Central Europe, which were generally warmer and more humid than at present. Floristically, the flora of the Tachov (Cheb–Domažlice) Graben seems to be comparable with the French 'Saugbagger-Flora' whereas the floras of the Pluto and Nero Clays show closer links to the Auenheim assemblage, stratigraphically assigned to Brunssumian (Zanclean, Early Pliocene) and Reuverian (Piacenzian, Late Pliocene), respectively. While our datasets do not show any significant differences between the results from the oldest flora of the Tachov (Cheb–Domažlice) Graben to the slightly younger Pluto and Nero Clays, datasets from Alsace presented by Teodoridis et al. (2009) potentially suggest a slight decrease of MAT and CMMT from the stratigraphically older 'Saugbagger-Flora' (MAT: 15.3–15.6 °C; CMMT: 2.7 °C; WMMT: 23.6–25.1°C; MAP: 979–1146 mm) to the Auenheim assemblage (MAT: 13.6–15.6 °C; CMMT: 0.9–1.7 °C; WMMT: 23.6–24.2°C; MAP: 979–1122 mm). Such differences might be explained by a spatial (longitudinal) differentiation of climate with warmer values further eastward and an earlier onset of Late Pliocene cooling in the western part of Central Europe. However, asynchrony of the floras seems to be more probable, especially when considering the poor age constraints of the floras on one hand and a probable forcing also of Pliocene climate and vegetation by eccentricity cycles on the other, as suggested by Popescu et al. (2006) for the Dacic Basin in Romania during 4.9 to 4.3 Ma.

Further quantitative climate data are available from the Lower Rhine Basin in NW Germany. For the Rotton Formation (Early Pliocene) CA analyses give values for MAT of 13.3 to 13.8 °C, for CMMT -0.1 to 4.1 °C, and for WMMT 21.1 to 26.4 °C (Hambach Rotton leaf flora – Utescher et al., 2000) and 14.1 to 14.4 °C (MAT), 1.8 to 2.7 °C (CMMT), 24.7 to 25.7 °C (Hambach Rotton carpo flora – Mosbrugger and Utescher, 1997). Floras from the Reuver Clay (carpoflora, Late Pliocene, method CA – Mosbrugger and Utescher, 1997) provide values of 13.8 to 13.9 °C (MAT) and 3.4 to 4.6 °C (CMMT) 24.7 to 24.8 °C (WWT), whereas floras from the Lower Pleistocene part of the succession give considerably lower values of 10.6 to 12.4 °C (MAT), -2.8 to 1.3 °C (CMMT), and 21.7 to 23.8 °C (WMMT) (Tegelen carpoflora, Tiglian C – MN17 /Gelasian/, method CA – Mosbrugger et al., 2005). Those latter values correspond well to our datasets from the upper part of the Nová Ves Member (lignite beds and upper part). Temperature parameters from the older floras of the Cheb Basin (Tachov /Cheb–Domažlice/ Graben, Pluto and Nero Clays) are clearly warmer than those from the Lower Rhine Basin, which are more similar to the data from Auenheim discussed above. This might indicate a latitudinal gradient of temperatures. Nevertheless, the general temporal development of temperatures with a clear cooling at the beginning of the Pleistocene in the Northern Rhine Basin (Mosbrugger et al., 2005) as well as in the global marine climate record (Zachos et al., 2001) seem to correlate with the results from the Cheb Basin (see Table 6, Fig. 10). However, precipitation data from the Lower Rhine Basin do not show any trend but stay around 1000 mm for the whole sequence. Values for the Rotton Formation (Early Pliocene) are MAP 897–1151 mm, LMP 42–49 mm, HMP 109–170 mm, WMP 47–53 mm (Hambach Rotton leaf flora, method CA – Utescher, et al. 2000) and MAP 979–1034 mm, LMP 42–43, HMP 124–139 mm, WMP 84–91 mm (Hambach Rotton carpoflora, method CA – Mosbrugger and Utescher, 1997). Floras from the Reuver Clay give very similar results of MAP 979–1076 mm, LMP 33–49 mm, HMP 115–127 mm, WMP 81–92 mm (carpoflora – Mosbrugger and Utescher, 1997). From the Lower Pleistocene level only MAP values are published with 1036-1080 mm (Tegelen carpoflora, Tiglian C – MN17, method CA – Mosbrugger et al., 2005).

Such regional differences of the temporal development in precipitation may well be due to the increasing continental character of climate in the eastern parts of Central Europe in pace with the Northern Hemisphere Glaciation (e.g., Sarnthein et al., 2009; Bruch et al., 2011).

Unfortunately, the lack of reliable age control for the studied sites as well as for parts of the floras available for comparison hinders for the moment a more insightful interpretation of the terrestrial climatic changes at the Pliocene/Pleistocene boundary in Central Europe. Especially the increasing influence of orbital cycles on the Pleistocene climate, i.e., the increased climatic forcing by obliquity and precession with the onset of the Early Pleistocene (Lisiecki and Raymo, 2007), needs to be taken into account and requires higher stratigraphic resolution. Such quantitative studies of Early Pleistocene pollen sequences in deed are able to detect temperature and precipitation changes in phase with obliquity driven climate cycles. For Southern Europe warmer and more humid than present day conditions during warm phases and close to present day conditions during cold phases are documented (e.g., Klotz et al., 2006; Fauquette and Bertini, 2003), whereas in Northern Europe during cold phases at least winter temperatures seem to be cooler than present (Pross et al., 2000; Pross and Klotz, 2002).

Nevertheless, our data consistently show temperatures and precipitation higher than today during the Pliocene and close to modern values in the younger levels, most probable at the beginning of the Pleistocene. There is little evidence for much colder than present day conditions as implied by Bůžek et al. (1985) by comparing the youngest flora with modern vegetation from the Taiga zone. However, the cold end of the resulting coexistence intervals may reflect such cold conditions which cannot be resolved in greater detail here. Still, as shown also by data from Southern Europe (Klotz et al., 2006; Fauquette and Bertini, 2003) temperatures cooler than present seem to be unlikely even during the cold phases of the earliest Pleistocene climatic cycles. This implies a general overestimation of the climatic forcing behind vegetation changes by such qualitative interpretations like the one of Bůžek et al. (1985). Or, to take it the other way, vegetation is reacting highly sensitively to environmental changes that may be only slight climatic shifts or also other factors than climate and hard to quantify.

7. Conclusions

The following bullet points conclude crucial results of this study:

- A new floristic analysis proved the original statement given by Bůžek et al. (1982, 1985) and corroborate a decreasing trend of exotic elements within the studied floras, i.e. from the older floras of the Tachov (Cheb–Domažlice) Graben related to Early Pliocene floras of central Europe, towards floras of the Pluto and Nero Clays with estimated ages of Late Pliocene (Piacenzian), to floras from the lignite beds and upper part of the Nová Ves Member characterised by a massive immigration of boreal elements.
- The results of IPR vegetation analysis indicate a vegetation transition from broad-leaved deciduous forests (Tachov /Cheb–Domažlice/ Graben) and/or ecotonal vegetation of mixed mesophytic forest / broad-leaved deciduous forests of the Pluto Clay (the Vonšov Member) and the Nero Clay (the Nová Ves Member) to “more open” light forests of the broad-leaved deciduous or mixed mesophytic types grown in areas of zonal to extrazonal uplands during the Nová Ves Member (lignite and upper beds) setting. This vegetation change is characterised by a distinct increase of abundances of SCL + LEG (11 %) and DRY HERB (16 %) components. The high percentage of herbaceous component exceeding 44 % in

the Nová Ves Member could indicate a close relation to the vegetation type of the Xeric grasslands or steppe. However, the relatively low value of DRY HERB component and a high proportion of arboreal BLD elements safely exclude this type of vegetation.

- The PCS approach displays the diversified information provided by three different palaeobotanical datasets. Studies on modern assemblages suggest that the carpological PCSs from wetland sediments, mainly deposited in low-energy environments, provide information on the local vegetation structure limited to the azonal component of vegetation. Along with the above-mentioned chronological vegetation trend the wetland communities show a slight but significant loss of exotic elements and point to the development of vegetation contexts more similar to present European ones.

- Palaeoclimatic signals derived from the CA analysis generally show warmer and more humid conditions than present day for the Pliocene levels and comparable values to the present for the youngest (early Pleistocene) level. CA results for the Vonšov Member give values about 15 °C for mean annual temperature, winter temperatures around 5 °C, summer temperatures about 25 °C, and an annual precipitation of more than 900 mm. CA-based palaeoclimate data for the Nová Ves Member show a decreasing trend in temperatures as well as in precipitation with a mean annual temperature of about 7 °C, winter temperatures well below zero (-3 °C), and summer temperatures of about 16° C in the upper part of the succession. This may indicate the beginning of a cooler phase at the end of the Pliocene and/or beginning of Pleistocene in the Bohemian Massif area.

There is no evidence for colder than present-day conditions as implied by Bůžek et al. (1985) by comparing the youngest flora with modern vegetation from the Taiga zone. Such a qualitative interpretation seems to overestimate the climatic forcing behind the observed vegetation changes.

Acknowledgements

We would like to thank to R. Stančíkové (Regional Office Pilsen, Czech Hydrometeorological Institute) and to D. Richterová (Regional Office Karlovy Vary, Czech Hydrometeorological Institute) for the access to the meteorological datasets of Cheb. The study was supported by the grant projects of GA ČR (Grant Agency of the Czech Republic) No. P210/10/0124 and the Ministry of Education, Youth and Sports (scheme MSM 002162085). This is a contribution to NECLIME (www.neclime.de) and ROCEEH (www.roceeh.net).

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Caption to tables and figures

Fig. 1a. Location of the studied floras of the Vildštejn Formation and Tachov (Cheb–Domažlice) Graben (modified after Bůžek et al., 1985).

Fig. 1b. Geological sections of selected drill cores and the Nová Ves clay pit. Symbols: A. Tachov (Cheb–Domažlice) Graben, B (I.) Vonšov Member (Pluto Clay), C (II.) Nová Ves Member (Nero Clay), D. (III.) Nová Ves Member (lignite beds), and E. (IV.) the Nová Ves Member (upper part), modified after Bůžek et al. (1985). Stratigraphic data after Bucha et al (1990) and Špičíková et al. (2000); GPTS dataset modified after Lourens et al. (1996) and Petronio et al. (2011).

Fig. 2. Simplified pollen diagrams of drill core HV 2 (a) and Nová Ves clay pit (b). The relative abundances of trees, shrubs and herbs, as well as the AP/NAP ratio are based on the sum of gymnosperm and angiosperm taxa excluding aquatic and hydrophytes to better reflect the regional vegetation. For all other taxa the total pollen sum served as the base for calculating percentages. For details and full taxa list see Appendix 1.

Fig. 3. Plant Community Scenario diagrams (PCSs) provided by carpological, leaf and pollen records from the Vildštejn Formation, stratigraphic level/horizon B (Vonšov Member – Pluto Clay). Notice that the PCSs do not represent actual reconstructions of the palaeoenvironment and palaeovegetation, rather they are a graphical representation of quantitative palaeobotanical data. Each typology of plant symbol is referred to a group of taxa that shares habitus, size and ecological features (Martinetto and Vassio, 2010; Vassio, 2012, Vassio and Martinetto, 2012). Fifty plant symbols and twenty-five taxa names, among

the most frequent floristic elements, have been reported into the diagram by taking into account their ecological requirement, expressed by the belts in different colour. The breadth of each belt is proportional to the frequency of plants classified as mesophytic, hygrophilous or aquatic in the fossil assemblage; also the proportion of different plant symbols reflects the frequencies of the taxa belonging to each ‘growth form’ group within the fossil assemblages (e.g., broad-leaved deciduous shrub short/medium/tall, broad-leaved deciduous tree short/medium/tall, evergreen conifer tree Pinaceae, aquatic submergent herb short/medium/tall etc.).

Fig. 4. Plant Community Scenario diagrams provided by carpological records from the Vildštejn Formation and Tachov (Cheb–Domažlice) Graben. Stratigraphical levels/horizons: A (Tachov /Cheb–Domažlice/ Graben), C (Nová Ves Member – Nero Clay), D (Nová Ves Member – lignite beds). For B (Vonšov Member – Pluto Clay), see Fig. 3

Fig. 5. Plant Community Scenario diagrams provided by pollen records from the Vildštejn Formation. Stratigraphic levels/horizons: C (Nová Ves Member – Nero Clay), D (Nová Ves Member – lignite beds), E (Nová Ves Member – upper part). For B (Vonšov Member – Pluto Clay), see Fig. 3.

Fig. 6. Plant Community Scenario diagrams (PCSs) provided by carpological records from the modern locality Orco 1 (San Benigno Canavese, NW Italy). – 1. vegetation-PCS obtained from the standing vegetation survey of the area (diameter length ca. 100 m) ahead of the small pond from where a fruit-bearing sediment sample was analysed. 2. vegetation-PCS obtained from the standing vegetation survey of a small wetland crossed by a brook, extended few

tens of meters ahead of the small pond. 3. deposit-PCS obtained from a modern fruit and seed assemblage buried in the silty sediments of the pond. The three PCSs clearly show that this fruit and seed assemblage provides a very local record of the vegetation: the aspect of the transect is similar to the wetland vegetation close to the pond, and the signal of the mesophytic woodland which grows just 20 m apart of the pond is not well recorded by the carpological assemblage.

Fig. 7. General vegetation changes and trends based on the IPR vegetation results of the studied floras from the Vildštejn Formation and Tachov (Cheb–Domažlice) Graben during the Late Pliocene to Early Pleistocene period. Symbols: % CONIFER (percentages of zonal and extrazonal conifers), % BLD (percentages of broad-leaved deciduous woody angiosperms), % BLE (percentages of broad-leaved evergreen woody angiosperms), % SCL+LEG (percentages of sclerophyllous woody and legume-like woody angiosperms), % DRY HERB (percentages of open woodland and grassland elements), % MESO HERB (percentages of mesophytic forest undergrowth elements), and % zonal herb (percentages of zonal herbaceous elements, = % DRY HERB + % MESO HERB). The parameters are calculated based on the equations 1–5. A (Tachov/Cheb–Domažlice/ Graben), B (Vonšov Member – Pluto Clay), C (Nová Ves Member – Nero Clay), D (Nová Ves Member – lignite beds).

Fig. 8. Palaeoclimatic quantification of temperature parameters based on the Coexistence Approach, for MAT (mean annual temperature), CMMT (mean temperature of the coldest month) and WMMT (mean temperature of the warmest month) derived from the Coexistence Approach (CA). Symbols: A (Tachov/Cheb–Domažlice/ Graben), B (Vonšov Member – Pluto Clay), C (Nová Ves Member – Nero Clay), D (Nová Ves Member – lignite

beds), E (Nová Ves Member – upper part), green square (based on macrofossil plant remnants), yellow circle (based on microfossil plant remnants), red rhomb (based on macro- and microfossil plant remnants), solid vertical lines (present day climatic data from the meteorological station of Cheb). For data source see Table 3.

Fig. 9 Palaeoclimatic quantification of temperature parameters based on the Coexistence Approach, forMAP (mean annual precipitation), HMP (precipitation of the driest month), LMP (precipitation of the driest month) and WMP (precipitation of the warmest month) derived from the Coexistence Approach (CA). Symbols: A (Tachov/Cheb–Domažlice/ Graben), B (Vonšov Member – Pluto Clay), C (Nová Ves Member – Nero Clay), D (Nová Ves Member – lignite beds), E (Nová Ves Member – upper part), green square (based on macrofossil plant remnants), yellow circle (based on microfossil plant remnants), red rhomb (based on macro- and microfossil plant remnants), solid vertical lines (present day climatic datasets from the meteorological station of Cheb). For data source see Table 3.

Fig. 10. Comparison of palaeoclimatic proxy data based on the Coexistence Approach (CA) from the studied floras of the Vildštejn Formation, Tachov (Cheb–Domažlice) Graben and selected Pliocene and Pleistocene floras of Europe . – Symbols: 1. Tachov (Cheb–Domažlice) Graben, 2. Frankfurt ‘Klärbeckenflora’ (Germany), 3. Gérce (Hungary), 4. Pula (Hungary), 5. Berga (Germany), 6. Willershausen (Germany), 7. Sessenheim (France), 8. Hambach Rotton (Germany) – leaf, 9. Hambach Rotton (Germany) – carpology, 10. Vonšov Beds (Pluto Clay), 11. Nová Ves Beds (Nero Clay), 12. Auenheim (France), 13. Reuver Clay (Germany), 14. Nová Ves Beds (lignite beds), 15. Nová Ves Beds (upper beds), and 16. Tegelen (the Netherlands).

Table 1. Summary of the floristic compositions of the studied floras of the Vildštejn Formation and Tachov (Cheb–Domažlice) Graben including suggested Nearest Living Relatives. Symbols: C (cone), F (fruit), L (leaf), P (pollen), S (seed), Sp (spore) and W (wood)

Table 2. Results of the IPR vegetation analysis from the studied floras of the Vildštejn Formation and Tachov (Cheb–Domažlice) Graben. Symbols: L (leaf flora), F (fruit and seed flora), P (pollen flora). Percentages of the BLD (broad-leaved deciduous woody angiosperms), BLE (broad-leaved evergreen woody angiosperms), SCL+LEG (sclerophyllous woody and legume-like woody angiosperms), DRY HERB (open woodland and grassland elements), MESO HERB (mesophytic forest undergrowth elements) components were calculated following the equations 1 to 4 .

Table 3. Results of the palaeoclimatic quantification based on the Coexistence Approach for the studied floras from the Vildštejn Formation and Tachov (Cheb–Domažlice) Graben including the limiting taxa of the coexistence intervals. Symbols: L (leaf flora), F (fruit and seed flora), P (pollen flora), MAT (mean annual temperature), CMMT (mean temperature of the coldest month), WMMT (mean temperature of the warmest month), MAP (mean annual precipitation), HMP (precipitation of the driest month), LMP (precipitation of the driest month) and WMP (precipitation of the warmest month). The source of climatic parameters from the meteorological station of Cheb is derived from the website of the Czech Hydrometeorological Institute (http://www.chmi.cz).

Table 4. Results of the palaeoclimatic quantification based on the Coexistence Approach for the studied fossiliferous horizons of drill core HV 2 and levels of Nová Ves clay pit (the Vildštejn Formation) based on micro (pollen) plant remains. Symbols: MAT (mean annual temperature), CMMT (mean temperature of the coldest month), WMMT (mean temperature of the warmest month), MAP (mean annual precipitation), HMP (highest monthly precipitation) LMP (lowest monthly precipitation) and (WMP) precipitation of the warmest month.

Table 5. Palaeoclimate proxy data of MAT (mean annual temperature) derived from Leaf Margin Analysis were calculated following the equations 5 to 7 as well as values of sampling errors (Eqs 8 to 9) and mean absolute deviation (Eq. 10). Symbols: *n* (total species number), *P* (proportion of *n* species with entire margin, $0 < P < 1$).

Appendix 1. Raw data pollen counts of drill core HV 2 and Nová Ves clay pit (Vildštejn Formation).

Appendix 2. List of acronyms, growth forms and plant symbols used within Plant Community Scenario (PCS). The symbol size for herbaceous plants are twice as large as they are drawn in the PCSs in order to make their visualization easier (modified after Vassio and Martinetto, 2012).

Appendix 3. Plant taxa occurring in the studied floras from the Vildštejn Formation and Tachov (Cheb–Domažlice) Graben and their scoring according to the IPR-vegetation analysis.

Appendix 4. Quantitative and qualitative datasets of Plant Community Scenario diagrams (PCSs) referred to floristic lists obtained by leaf, pollen and carpological record analyses within Vildštejn Formation (Table 1) and by actuopalaeobotanical analysis on carpological assemblages in modern sediments from NW Italy, Orco 1 (Fig. 6) – details in Vassio (2012). The datasets comprise also calculation useful in PCS construction on the basis of absolute quantitative data (column A) transformed into percentages (column X (%)). The percent values are summed up by grouping taxa a) belonging to the same ecological zone in order to obtain the X, M, HY and A zone extension within the PCS transects (X – xerophytic, M – mesophytic, HY – hygrophilous, A – aquatic); b) with the same growth form in order to define how many plant symbols of each type to be drawn in the PCS (see Appendix 2, modified after Vassio, 2012 and Vassio and Martinetto, 2012). ‘Plant organs’ column abbreviations: S (seed), F (fruit), Sp (spore), mC (male cone), Cs (cone scale), L (leaf), P (pollen).