Acta Palaeobotanica 66(1), 67–82, 2026
https://doi.org/10.35535/acpa-2026-0004

e-ISSN 2082-0259
ISSN 0001-6594

Palynostratigraphy as an alternative for absolute short-lived isotopes dating: revised chronology of Krzywce Wielkie littoral cores

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Received 15 January 2026; accepted for publication 11 May 2026

ABSTRACT. Five sediment cores were collected from Lake Krzywce Wielkie (‘Bory Tucholskie’ National Park) to reconstruct macrophytes succession: four from the littoral zone (35 cm) and one from deep water. Chronology originally published by Milecka and co-authors was established using radiocarbon dating for the deep-water core and short-lived isotopes for the littoral cores. Initial estimates suggested that the upper 13–20 cm of littoral sediments represented the last century; however, inconsistencies in ^{210}Pb and ^{137}Cs dating, combined with pollen evidence of sedimentary gaps, necessitated a revision of this timespan. Principal Coordinates Analysis was applied to align pollen sequences from littoral cores with those from the deep-water core, which has a well-established ^{14}C-based chronology. Twenty-five biplots representing three datasets (ALL set – all terrestrial taxa; PB set – terrestrial excluding *Pinus* and *Betula*; NAP set – herb taxa) and various core combinations facilitated the development of a revised chronology. Palynostratigraphic correlation provided tentative yet robust age estimates and revealed substantial sedimentary gaps – exceeding one millennium in one core and approximately two centuries in others. Three cores exhibited similar sedimentation patterns, distinct from the fourth. Overall, the chronological addendum presented by Milecka and co-authors demonstrated that littoral sediments are considerably older than indicated by isotope dating.

KEYWORDS: lake sediments, chronology, palynostratigraphy, core correlation, sedimentary gap, ordination, PCoA

INTRODUCTION

Sediment cores for palaeolimnological studies are typically collected from the deeper parts of lakes to minimize disruption of sedimentary sequences caused by wave action and water-level fluctuations. Such disturbances may inhibit deposition below the sedimentary limit or even erode upper layers (Digerfeldt, 1986; Håkanson and Jansson, 2002). Because sedimentation processes in the shallow littoral zone are highly vulnerable to both natural and anthropogenic influences, interpreting littoral succession and its chronostratigraphy remains particularly challenging. However, when the objective is to reconstruct macrophyte succession, coring depth must correspond to the depth range of the target species. For instance, Brzozowski et al. (2021) collected cores along a transect spanning the minimum and maximum depths (1–3 m) of *Lychnothamnus barbatus* stands. In such cases, researchers must contend with the inherent unpredictability of littoral sediments.

Accurate sediment chronologies are essential for interpreting sedimentary archives (Bennett and Buck, 2016). Under conditions of continuous deposition, a robust event chronology can be established using isotopic methods, and varved sediments may even allow dating with annual precision (Tylmann et al., 2016). In shallow littoral environments, however, age estimates derived from isotopic techniques are highly uncertain, particularly

Publisher: W. Szafer Institute of Botany, Polish Academy of Sciences

where sedimentary gaps occur. Such discontinuities also complicate the correlation of multiple littoral cores. Furthermore, dating the youngest sediments using ^{210}Pb and ^{137}Cs isotopes (Appleby, 2002) rarely yields unequivocal results without independent validation (Walker, 2005), even in deep-water cores (Oldfield et al., 2003; Tylmann et al., 2016). The interpretative challenges discussed in this paper also illustrated this issue.

One potential method for validating sediment chronologies is palynostratigraphy. The use of pollen stratigraphy for age determination – or, in its early applications, for correlating sediment sequences – was pioneered by von Post (1916). This relative dating technique enabled synchronization of sediment layers across different cores. Pollen analysis as a chronostratigraphic tool remains widely employed for sediments older than the radiocarbon dating limit (approximately 40,000 years; e.g. Pidek, 2015), although for Holocene deposits it has largely been supplanted by radiocarbon dating, introduced by Libby (1955). Nevertheless, pollen stratigraphy continues to provide valuable means of assessing the accuracy and reliability of radiocarbon dates (Davis, 1984), particularly given the interpretative challenges associated with radiocarbon dating for the most recent centuries (Björck and Wohlfarth, 2002). For instance, Brzozowski et al. (2021) reported three markedly different radiocarbon ages obtained from macrofossils in the basal samples of three 30 cm long cores collected at depths of 1–3 m. Similarly, unpublished data from a project involving the author indicate substantial variability in such dates.

A new site of *Lobelia dortmanna* was recently discovered in Lake Krzywce Wielkie (Bory Tucholskie National Park), prompting an attempt to reconstruct the species' succession (Milecka et al., 2021). Because this plant occurs in shallow waters, material for palaeoecological analysis was collected from the littoral zone, comprising four cores taken at a depth of approximately 0.5 m. Their chronology was established using ^{210}Pb and ^{137}Cs isotopes, which indicated a young age of sediments in all analysed cores, however, the results were uncertain and suggested sediment mixing. A deep-water core collected for comparison (Milecka and Tobolski, 2015) was dated using radiocarbon methods.

Pollen analysis of the littoral cores revealed substantial differences in pollen spectra between cores 1, 2, 4 and core 3. Confronted with two possible interpretations, Milecka et al. (2021) adopted the chronology indicated by isotopic dating. However, the K3 core – almost devoid of anthropogenic indicators – suggested a much older sediment age, most likely due to removal of its uppermost layer. Given the inherent difficulties in dating littoral cores, an opportunity arose to validate the isotopically derived chronostratigraphy by examining the similarity of pollen spectra among littoral samples and comparing them with those from the deep-water core, which is continuous and has a well-established chronology. Consequently, the objective of this research became the revision of littoral-core chronology through numerical correlation of vegetational events recorded in deep-water and littoral sequences. This approach was expected to enable core correlation, reveal potential sedimentary gaps, and provide approximate age estimates for entire littoral cores rather than only their surface layers.

METHODS

Radiocarbon dating was used to prepare chronology of deep water core. 6 samples of macroremains of *Betula*, *Pinus* and *Sphagnum* were dated. Details are described in Milecka and Tobolski (2015). Recalibration of published dates was performed in OxCal v4.4 (Bronk Ramsey, 2009) and IntCal20 (Reimer et al., 2020), and the results are presented in Table S1 (Supplementary File 1[1]). Radiometric methods of short-lived isotopes ^{210}Pb and ^{137}Cs were applied as dating methods of littoral cores. Details are described in Milecka et al. (2021).

The differentiation of Local Pollen Assemblage Zones (LPAZs) depends on the relationships among selected terrestrial taxa: trees, shrubs (AP) and herbs (NAP), including human activity indicators (HI). Telmatophytes and aquatics are not considered. The general information on the pollen diagram also includes *Pinus* and *Betula* curves, which are significantly represented because of the regional specificity of the vegetation zone, contemporary human-induced changes in land use and abundance of pollination.

Therefore, three data sets were defined for comparison: (1) a set of 44 mainly terrestrial taxa, including those represented in at least three samples (data set referred to as ALL); (2) because the most abundant tree taxa influenced stratigraphic interpretation ambiguously – as discussed in detail in the Results

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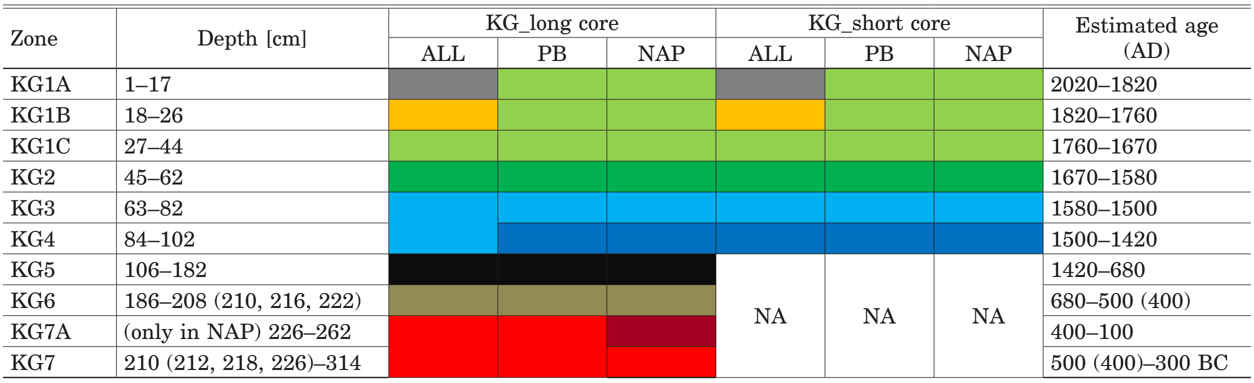
[1] Supplementary File 1: Table S1. Results of radiocarbon dating of macrofossils from the Lake Krzywce Wielkie, calibration in OxCal v4.4 (Bronk Ramsey, 2009) and IntCal20 (Reimer et al., 2020)

Table 1. Zones for deep core KG_long. Estimated age acc. to Milecka and Tobolski (2015); NA – data not available



Zone	Depth [cm]	KG_long core			KG_short core			Estimated age (AD)
		ALL	PB	NAP	ALL	PB	NAP	
KG1A	1–17	▨	🟩	🟩	▨	🟩	🟩	2020–1820
KG1B	18–26	🟧	🟩	🟩	🟧	🟩	🟩	1820–1760
KG1C	27–44	🟩	🟩	🟩	🟩	🟩	🟩	1760–1670
KG2	45–62	🟢	🟢	🟢	🟢	🟢	🟢	1670–1580
KG3	63–82	🟦	🟦	🟦	🟦	🟦	🟦	1580–1500
KG4	84–102		🔷	🔷	🔷	🔷	🔷	1500–1420
KG5	106–182	⬛	⬛	⬛	NA	NA	NA	1420–680
KG6	186–208 (210, 216, 222)	🟫	🟫	🟫				680–500 (400)
KG7A	(only in NAP) 226–262	🟥	🟥	🔴				400–100
KG7	210 (212, 218, 226)–314			🟥				500 (400)–300 BC

– analyses were also performed for the ALL set without *Pinus* and *Betula* (data set referred to as PB); and (3) a set comprising only herbaceous taxa (data set referred to as NAP).

As a correlation tool, an ordination method, PCoA with Bray-Curtis dissimilarity, was applied. All ordinations were prepared in R (R Core Team, 2020) vegan package (Oksanen et al., 2025) (functions vegdist(), cmdscale(), ordiplot()) and modified in CorelDraw X16. The proportion of explained variation for two first axes was calculated using only the positive eigenvalues. Negative eigenvalues were negligible compared with positive eigenvalues, being several orders of magnitude smaller. Both samples and species were presented on biplots.

Ordinations were carried out separately for the deep-water core (KG) or their respective parts, and for the littoral cores (K1–K4): (1) KG_long (268 samples from depths of 1–314 cm); (2) KG_short (88 samples from depths of 1–102 cm), because preliminary analyses indicated relationships between samples from cores K1, K2, and K4 and this section of the core; and (3) K1–K4 (30 samples). The effect of including samples deeper than 314 cm (KG_full core – 287 samples from depths of 1–600 cm) on the PCoA results was also assessed. As the changes were negligible, these deeper samples were not considered in further analyses.

Then, in order to detect similarities between KG core samples and littoral cores and to correlate them, ordinations were made for the set of all 388 samples (KG_long + K1–K4) and for a set of 208 samples (KG_short + K1–K4). Additionally, comparisons of the KG core and K1, K2, and K4 were performed, excluding the diverse K3.

The shared zones defined for the deep and littoral cores – neither local PAZs (delimited for a single core) nor regional PAZs (compiled for a region from multiple LPAZs) – were termed 'Lake PAZ' (abbreviated as LaPAZ), as they represent the evolution of the entire lake. Lake PAZ's were derived by visual inspection of ordination results, identifying the largest discontinuities. For easier interpretation of zones in the KG core, lines connecting neighbouring samples in stratigraphical order within each zone were drawn in specific colours (Figs 1–5 and Figs S1–S20: Supplementary File 2[2]). In subzones, lines were drawn without breaks, in different colours representing the subzones. Outlier samples located between zones are shown in magenta. The biplots for the littoral cores are shown as filled polygons (hulls) connecting the samples from individual levels. The same colour was applied to tables in the text and figures. Sample numbers of the KG core in biplots are shown in black, and those of littoral cores in the colours of their respective hulls.

RESULTS

ZONATION OF CORES

The resulting biplots (Figs 1–5 and Figs S1–S20) enabled a stratigraphic reinterpretation of littoral sediments and the correlation of samples across all analysed cores. Eigenvalues of the first two components (Table S2 – Supplementary File 3[3]) accounted for between 50% and 80% of the total variance. Higher values were obtained for KG_long than for KG_short, whereas the choice of data set did not influence the outcome.

KG core

PCoA of KG_long (ALL data set; Fig. 1) revealed a clear gradient within the dataset. Positive values on axis 1 primarily represented deciduous trees, whereas negative values corresponded to anthropogenic indicators together with *Juniperus*. Perpendicular to this gradient, a second gradient – *Pinus-Betula* – was evident. The taxa forming this second gradient were the most abundant and, more importantly, exhibited irregular variability, strongly influencing the analysis outcome and prompting separate analyses on the data set excluding these taxa (PB; Fig. S1). All subdivisions in the KG_long core showed the most distinct boundary at

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[2] Supplementary File 2: Figs S1–S20. PCoA biplot of Bray–Curtis dissimilarity

[3] Supplementary File 3: Table S2. Eigenvalues of PCoA ordination

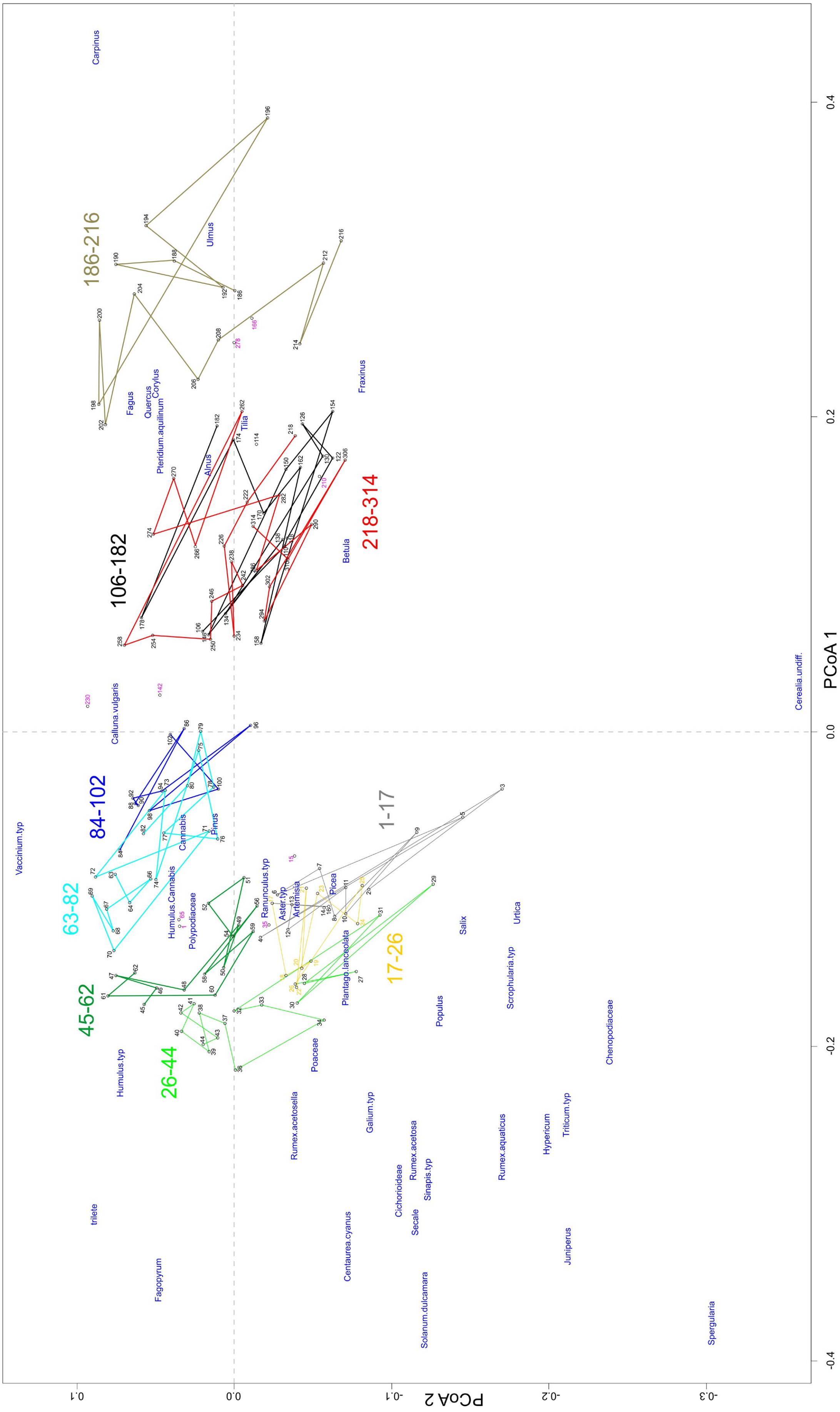

Figure 1. PCoA biplot of Bray–Curtis dissimilarity for the ALL set in KG_long core

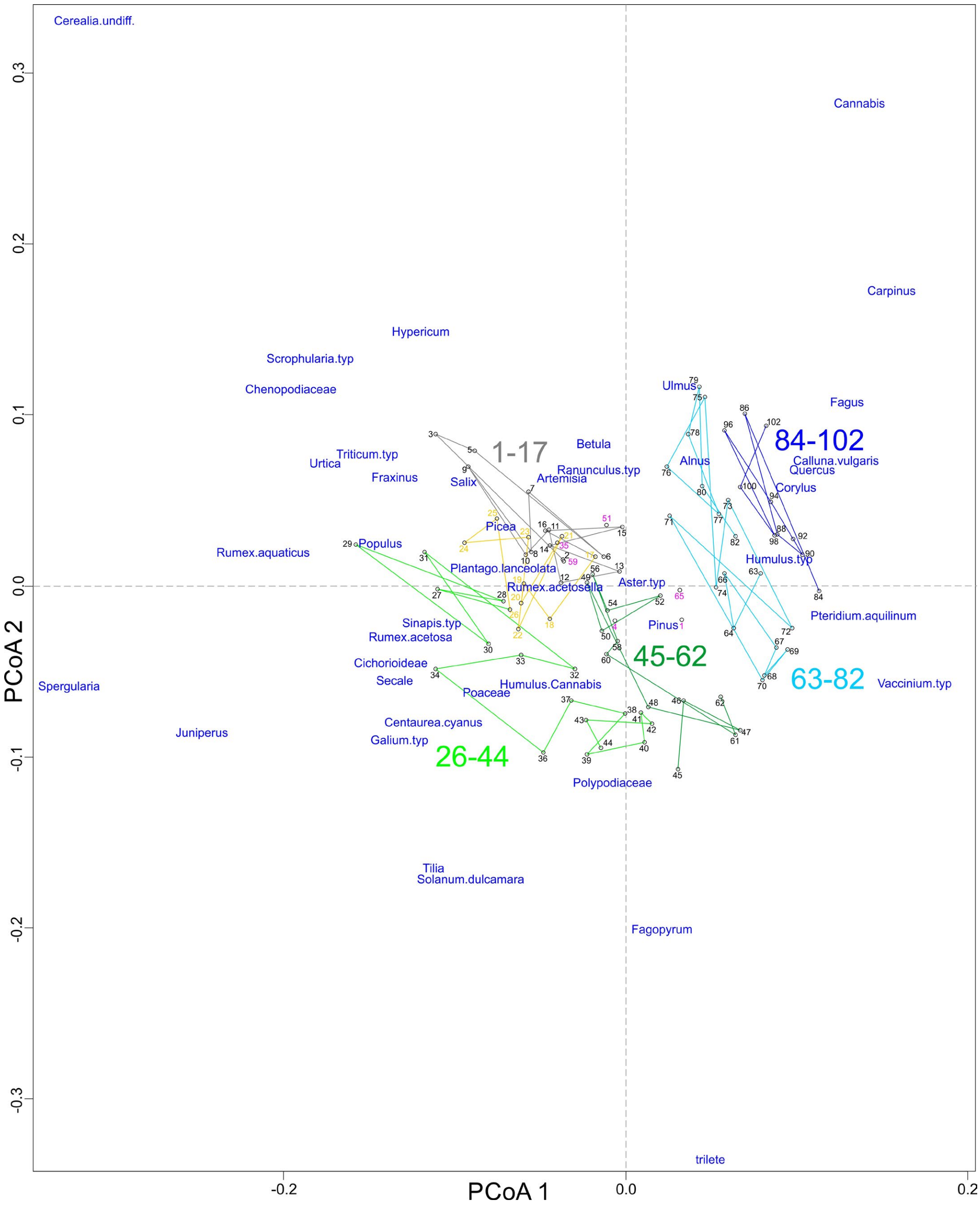

Figure 2. PCoA biplot of Bray–Curtis dissimilarity for ALL set in KG_short core

102/106 cm. Ultimately, four zones were distinguished in the upper part (with subzones 1A–1C) and three in the lower part (zones 5–7), along with subzone KG7A identified in the PCoA of KG_long_NAP (Fig. S2; Table 1).

In the lower section (106–314 cm), zone KG6 (186–208 [222] cm) was clearly distinguished from the overlying and underlying zones KG5 and KG7, which could not be differentiated from each other. Zone KG6 was characterised by the highest proportion of *Carpinus* in the samples. In the ordination of the KG_long core for the NAP data set, subzone LaPAZ-7A was identified, comprising samples from 226–262 cm. However, there is a substantial difference between the subdivisions in ALL and PB compared with NAP, because in the latter, it is impossible to distinguish zones below 182 cm, except for the aforementioned subzone, which separates these samples.

In the upper section, the only distinct boundary in each of the six subdivisions (Figs 1, 2 and Figs S1–S4) lies between KG2 and KG3 (62/63 cm). Samples at 61 and 62 cm in the KG_long_ALL subdivisions belong to LaPAZ-2; in KG_long_PB, they are intermediate between zones; and in KG_long_NAP, they fall within KG3. Other boundaries were distinguishable in some analyses, but were either diffuse or not identified at all. Several samples

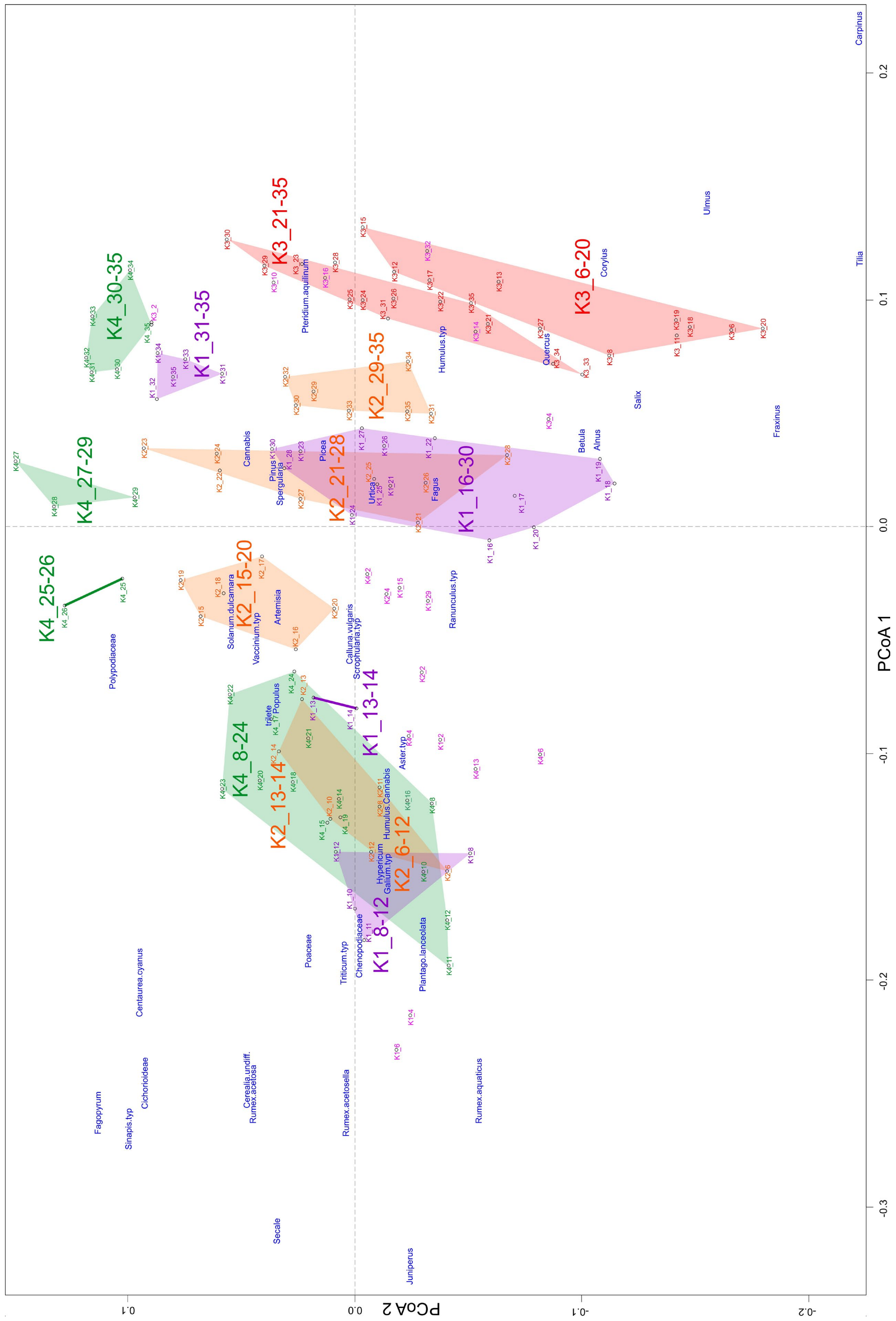

Figure 3. PCoA biplot of Bray–Curtis dissimilarity for ALL set in K1-K4 cores

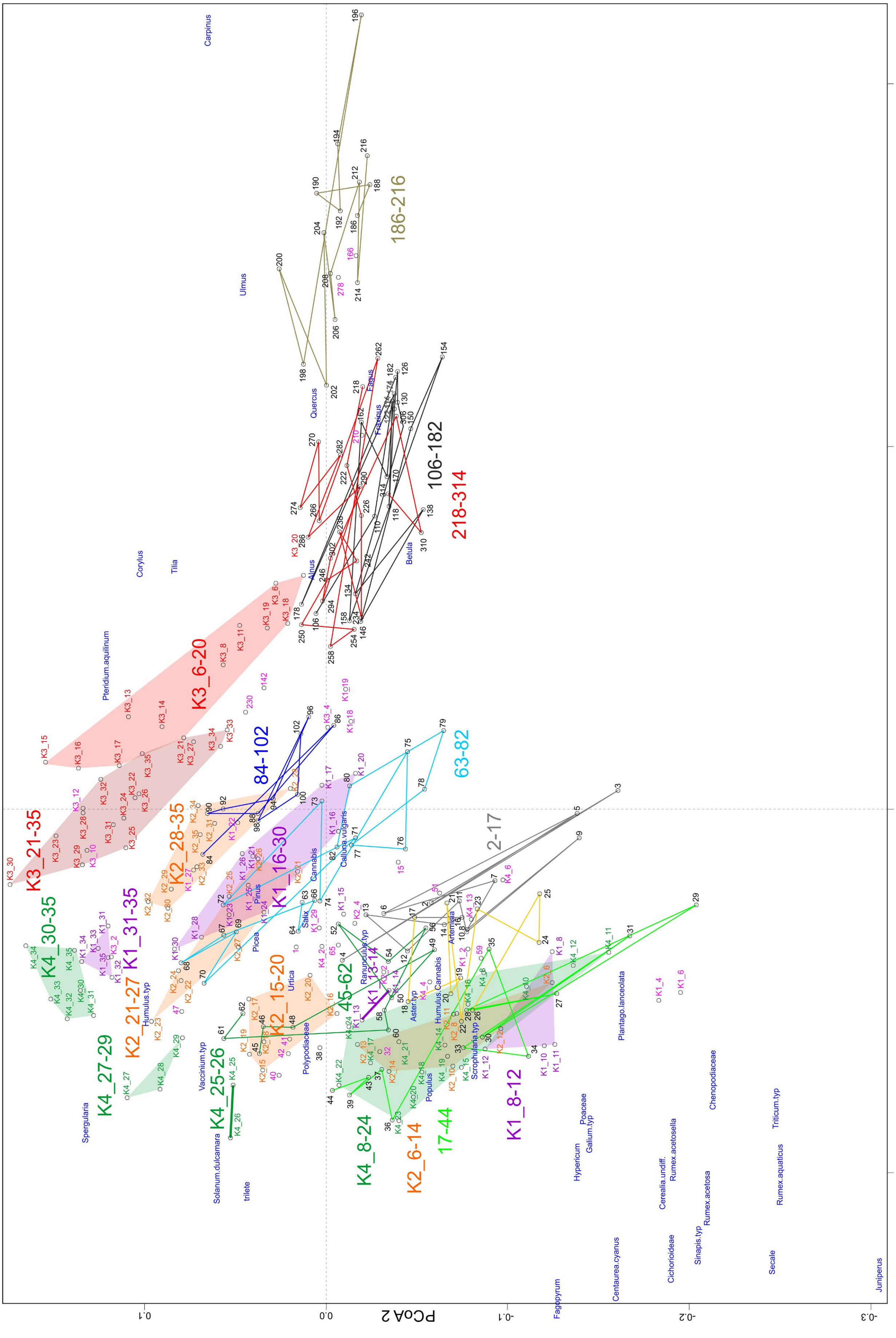

Figure 4. PCoA biplot of Bray–Curtis dissimilarity for ALL set in cores KG_long & K1–K4

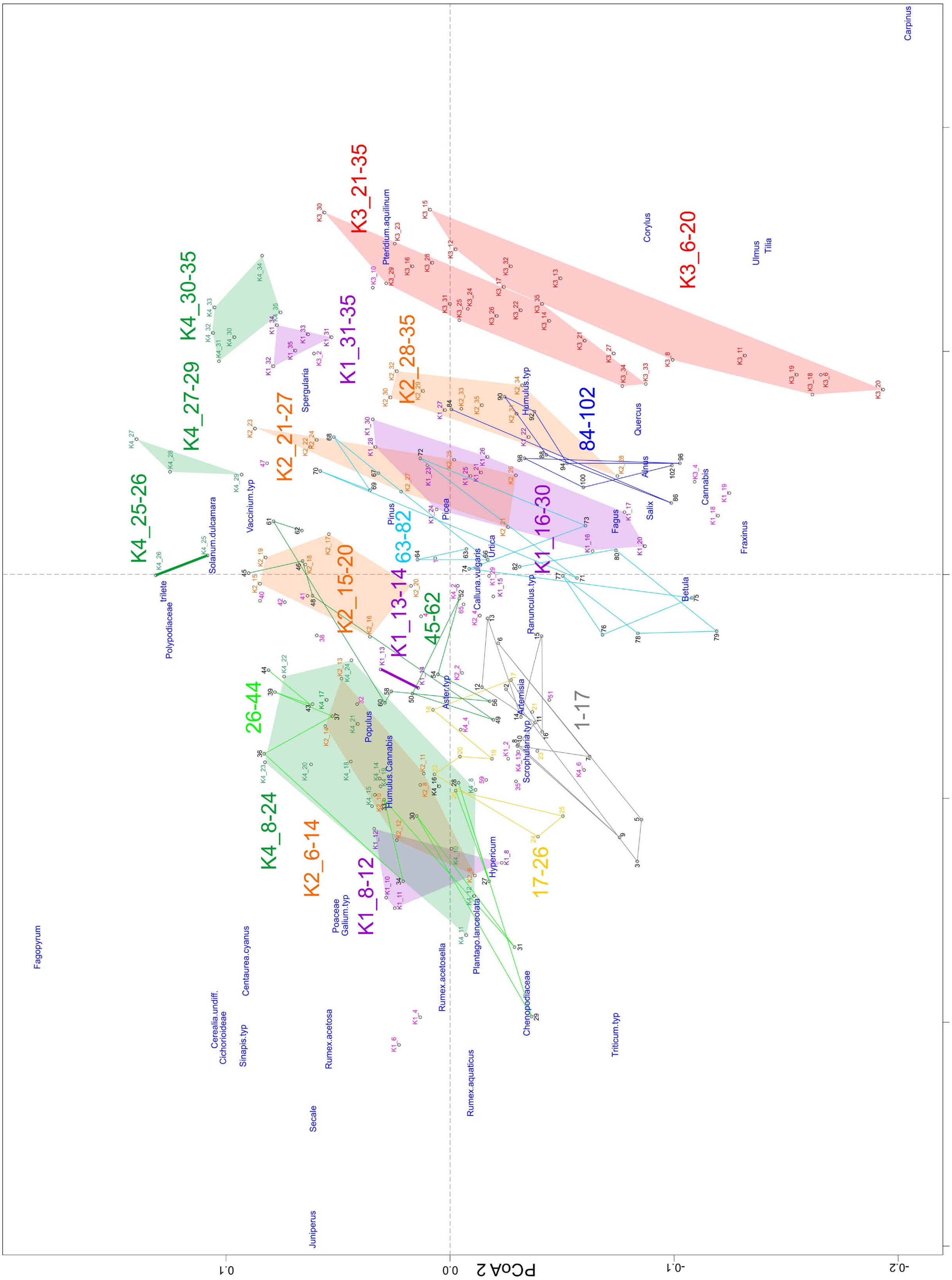

Figure 5. PCoA biplot of Bray–Curtis dissimilarity for ALL set in cores KG_short & K1–K4

contribute to these diffuse boundaries. Zones KG1 and KG2 are clearly separated only in KG_long_NAP and in KG_short_PB and NAP. In analyses of the ALL set, they can also be distinguished, but the distance between zones is small. In these analyses, it was also possible to subdivide KG1 into subzones A–B–C, where subzone B includes samples similar to both subzone A and subzone C. In KG_short, subzones of KG1 can be distinguished in every type of analysis. The divisions between KG3 and KG4 are very clear in all analyses of KG_long and KG_short, except in KG_long_ALL, where the zones partially overlap.

Visual subdivisions based on PCoA were compared with the zonation of pollen diagrams produced by stratigraphically constrained CONISS. The subdivisions in the lower part are consistent in PB and NAP and shifted by one sample in ALL. In the upper part, particularly in zones KG1 and KG2, greater discrepancies are observed.

Littoral cores

In cores K1, K2, and K4 (Figs S5, S6, S8), four distinct zones (L1–L4; Table 2) were identified. In core 1 (Fig. S5), sample groups 16–20 and 21–30 were combined with outlier samples 15 and 29 to form a single zone. In core 3, only two zones were distinguished (Fig. S7). In addition, 1–3 surface samples in each core were identified as outliers.

PCoA analysis performed simultaneously for all littoral cores using the ALL dataset (Fig. 3 and Figs S9, S10) indicated similarity among zones in cores K1, K2, and K4, and distinctiveness of samples from core K3. For cores K1, K2, and K4, the common zones identified across the littoral cores correspond to those distinguished within individual cores (Figs S5, S6, S8). In core K3, the boundary between zones lies at 20/21 cm, although in the NAP data set, this boundary cannot be defined. The assignment of zone K1_13–14 to L2 in the analysis of all four littoral cores for the ALL dataset (Fig. 3) may appear controversial at first glance; however, analyses for the remaining datasets and subsequent core alignments justify this interpretation.

CORE CORRELATION

Core matching began with PCoA analyses on the ALL data set for littoral cores and the KG_long core. This analysis (Fig. 4) revealed that samples from K1, K2, and K4 exhibit similarity to KG_long samples from 1–102 cm, whereas samples from core K3 show no similarity to any KG samples. Consequently, further analyses were conducted on KG_short + littoral cores K1, K2, and K4 (Figs S11–S13) and on KG_short + all littoral cores simultaneously, both including (Fig. 5) and excluding samples from core K3 (Fig. S14). Individual core matching (Table 3) produced relatively clear results for core K2 (Fig. S12), moderately clear results for K1 (Fig. S11), and ambiguous results for K4 (Fig. S13).

Table 2. Zones identified for littoral cores

Littoral Zones	K1 [cm]	K2 [cm]	K4 [cm]
L1	8–12	6–14	8–24
L2	13–14	15–20	25–26
L3	15–30	21–28	27–29
L4	31–35	29–35	30–35

LaPAZ-1

In cores K1, K2 and K4 (Figs S11–S13), similarity was demonstrated between samples from zone L1 and those from zone KG1C. Likewise, in every core, it was shown that subzones KG1A-B (1-17-26 cm) exhibit no similarity to any zone of the littoral cores. These findings are confirmed by PCoA for all littoral cores (Fig. 5 and Fig. S14).

The analysis of KG_long_PB (Fig. S15) clearly separates LaPAZ-1 from LaPAZ-2 in the littoral cores, but does not allow differentiation of KG1 subzones. Zones KG1 and KG2 also partially overlap. In contrast, the analogous analysis for KG_short_PB (Fig. S16) distinctly separates zones L1 and L2. Finally, the same analysis for KG_short, restricted to cores K1, K2 and K4, enables linking zone L1 of the littoral cores with subzone KG1C (Fig. S17).

The analysis performed on the NAP data set for KG_long (Fig. S18) indicates a systematic shift of zones L1–L4 of the KG core relative to the littoral cores, such that littoral samples plot between KG zones. This shift disappears only at zone L4. Differentiation of subzones within KG1 is not possible, but separation from LaPAZ-2 is clear for all cores. Analogous

Table 3. Summary of similarities between samples from the KG_long core and the littoral cores. Numbers in parentheses indicate the range of KG samples [cm] showing the greatest similarity to a given littoral zone

Littoral core	KG1A 1–17	KG1B 17–26	KG1C 26–44	KG2 45–62	KG3 63–82	KG4 84–102
K1	–	–	L1(26–34)	L2(48–60)	L3	L4
K2	–	–	L1(26–37)	L2(45–48)	L3(63–72)	L4(84–100)
K4	–	–	L1(26–44)	L2(45–48)	?	?

conclusions follow from PCoA for KG_short + K1–K4 (Fig. S19) and for KG_short + K1, K2, K4 (Fig. S20). The latter analysis, similarly as in Fig. S17, allows zone L1 of the littoral cores to be linked with subzone KG1C.

LaPAZ-2

Samples from the KG2 zone clearly correspond to the L2 zone in cores K1, K2 and K4 (Figs 4, 5 and Figs S11–S13), although K4 deviates slightly from the others. The analysis of the PB data set for KG_short clearly links KG2 with L2 zones across all cores (Figs S15–S17). The analysis of the NAP data set does not show the previously described shift for the K4 core, reveals a slight shift for the K1 core, and a pronounced shift for the K2 core (Figs S17–S20).

LaPAZ-3

Zone LaPAZ-3 is somewhat more challenging to interpret. While the PCoA for the ALL dataset on KG_long (Fig. 4) allows a clear association of this KG zone with the corresponding core zones K1 and K2, the linkage within core K4 is weaker.

In core K1 (Fig. S11), zones 16–20 and 21–30 were not separated (in the same manner as in Fig. S5), making it difficult to determine the precise relationship between KG3 and L3. In core K2 (Fig. S12), zone L3 can be unequivocally associated with zone KG3. In the case of core K4, it is more similar to KG2 than to KG3 (Fig. S13). However, analyses of the relationships between all littoral cores (or excluding K3) and KG_short (Fig. 5 and Fig. S14) also enable a clear linkage between L3 and KG3.

In the PB dataset (Figs S15–S17), there is a connection between KG3 and L3 in core K2 (the strongest association across all variants), whereas K4 shifts towards KG2 and K1 towards KG4.

In the NAP dataset (Figs S18–S20), there is a linkage between KG3 and zone L3 in core K4 (the strongest association across all variants), weaker for K2, while core K1 again deviates, shifting towards KG4.

LaPAZ-4

Zone KG4 can be unequivocally associated only with L4 in core K2 within the ALL dataset (Figs 4, 5 and Figs S12, S14). The analysis of KG_long_PB (Fig. S15) links zone KG4 with zone L3 of the K1 core. Conversely, the analysis of KG_short_PB (Figs S16, S17) clearly associates zone L4 of littoral cores K1, K2 and K4 with KG4. The NAP dataset (Figs S18–S20) also links KG4 with L4 in cores K1 and K2.

For zone L4 in core K4, evidence suggests a considerably older age. The analysis of the NAP dataset indicates its similarity to the distinguished subzone KG7A, i.e. samples from core KG at depths of 226–262 cm (Fig. S18). Across all diagrams based on both herbaceous and arboreal taxa (except Fig. S16), zone L4 of core K4 was the most divergent from the ranges of KG zones in the upper part of the core.

REVISION OF LITTORAL CORES CHRONOLOGY

Figure 6 presents a graphical summary of correlated zones in deep and littoral cores, together with a robust chronology for the KG-core. The resulting PCoA biplots reveale a strong similarity between samples from littoral cores K1, K2, and K4 and those from KG_short. This allows the basal age of the littoral cores to be estimated at no later than the beginning of the 15th century. The sedimentation rate would therefore average approximately 0.6 mm/year, which is consistent with results obtained for other oligo-mezotrophic lakes. The age of the LaPAZ-1/LaPAZ-2 boundary, which Milecka et al. (2021) determined based on isotopic dating at ~1900 AD, was estimated here at ~1670 AD, nearly three times older. In turn, the age of the LaPAZ-2/LaPAZ-3 boundary was established as the end of the 16th century. Although littoral cores K1, K2, and K4 exhibit a similar sedimentation pattern, they differ in the rate within specific stratigraphic zones. On the other hand, PCoA biplots presented in Figs 4, 5 and Figs S11–S13, S17, and S20 indicate that samples from zone L1 correspond to zone KG1B-C, i.e. only from 26 cm depth, dated to the mid-19th century. This suggests the existence of a sedimentary hiatus in these three cores.

While the zones of cores K1, K2, and K4 follow a stratigraphic order on PCoA biplots, the two distinguished zones in core K3 either reverse this order or show no stratigraphic pattern at all, e.g. Figs S10 and S18. The PCoA biplot for the ALL dataset (Fig. 4) indicates a greater similarity of younger samples from core K3 (zone 6–20 cm) to older samples from core KG, whereas surface samples (K3_2 and K3_4) cluster within LaPAZ-4, clearly deviating from the rest of the core. In ordination based on the PB dataset (Fig. S15), surface samples also fall within LaPAZ-4 of core K4, while the younger zone of core K3 shows strong affinity to KG5 and KG7, whereas the hornbeam zone (186–208 cm) is markedly distinct and highly dissimilar to other samples, similar to the ALL dataset. In both ALL and PB, it is impossible to determine whether samples from core K3 should be linked to the youngest or the oldest zone of the lower part of core KG.

The relationship appears different in the NAP diagram (Fig. S18), which shows the greatest similarity of the entire K3 core to KG6 and KG7, i.e. samples from 186–314 cm. Based on the *Carpinus* curves, I suggest that this refers to samples from 262–314 cm, corresponding to the Roman period (~100 AD–300 BC). While the older age of K3 compared to LaPAZ-1–LaPAZ-4 is certain, a more precise correlation remains highly uncertain; nevertheless, the record preserved in K3 allows for an alternative interpretation of the data.

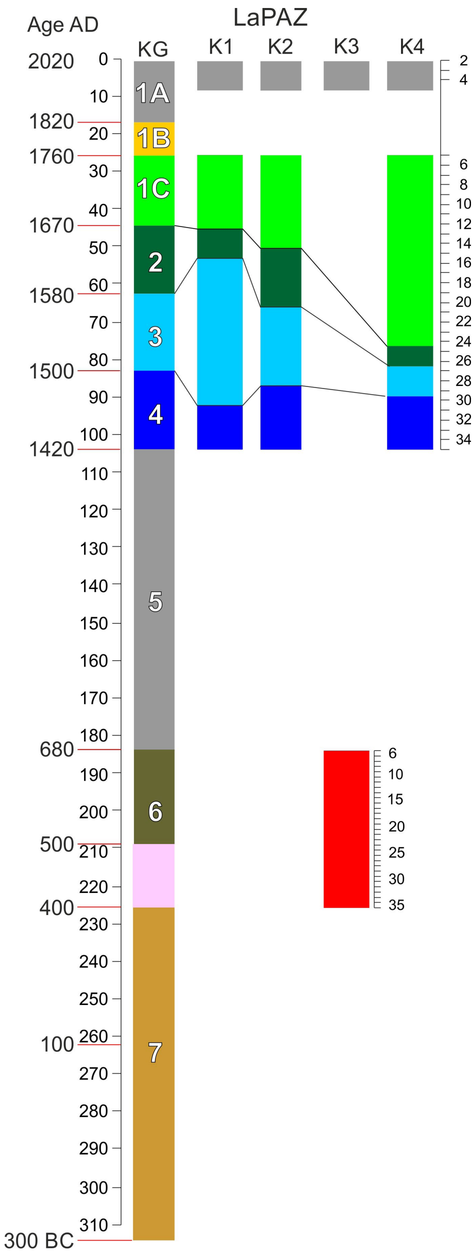

Figure 6. Graphical summary of correlated zones in deep and littoral cores together with robust chronology of KG-core.

It cannot be ruled out that the sediment of this core, due to its past location in a shallower part of the lake compared with other littoral cores, was more frequently affected by disturbances in sedimentation processes throughout its history, resulting in its specific character and preventing synchronisation based on sample similarity.

This inference is supported by analyses of mean values and ranges for selected taxa or their groups in core K3 (Fig. 7). Core K3 is clearly distinctive from other littoral cores across all pollen spectrum classes: trees and shrubs, Poaceae, human indicators, cereals, and herbs. In the latter class, this distinctiveness is least pronounced, as is the differentiation of K3 zones. Minimal percentages of Poaceae and human indicators, along with the near absence of cereal pollen in K3, indicate the greatest similarity to zone KG7. Among trees, the distinguishing components are deciduous taxa, whereas the proportions of *Pinus* and *Betula* do not differentiate K3 from other littoral cores.

To improve comparability of tree percentages across sediment groups, the relative share of taxa and their groups was calculated against the sum of trees only ('/Trees' in Fig. 7). Under this approach, K3 also shows clear distinctiveness from littoral cores for *Pinus* and for the combined *Pinus* and *Betula*, confirming its greatest similarity to zone KG7. The sediment of core K3 would therefore have accumulated primarily during the Roman period.

DISCUSSION

Core correlation based on pollen sequences is not always straightforward; consequently, visual or graphical approaches are still widely employed (Thomson et al., 2012). Correlation can be performed either on the basis of differentiated pollen zones or by examining the (dis)similarity of individual samples. This can be done visually or numerically.

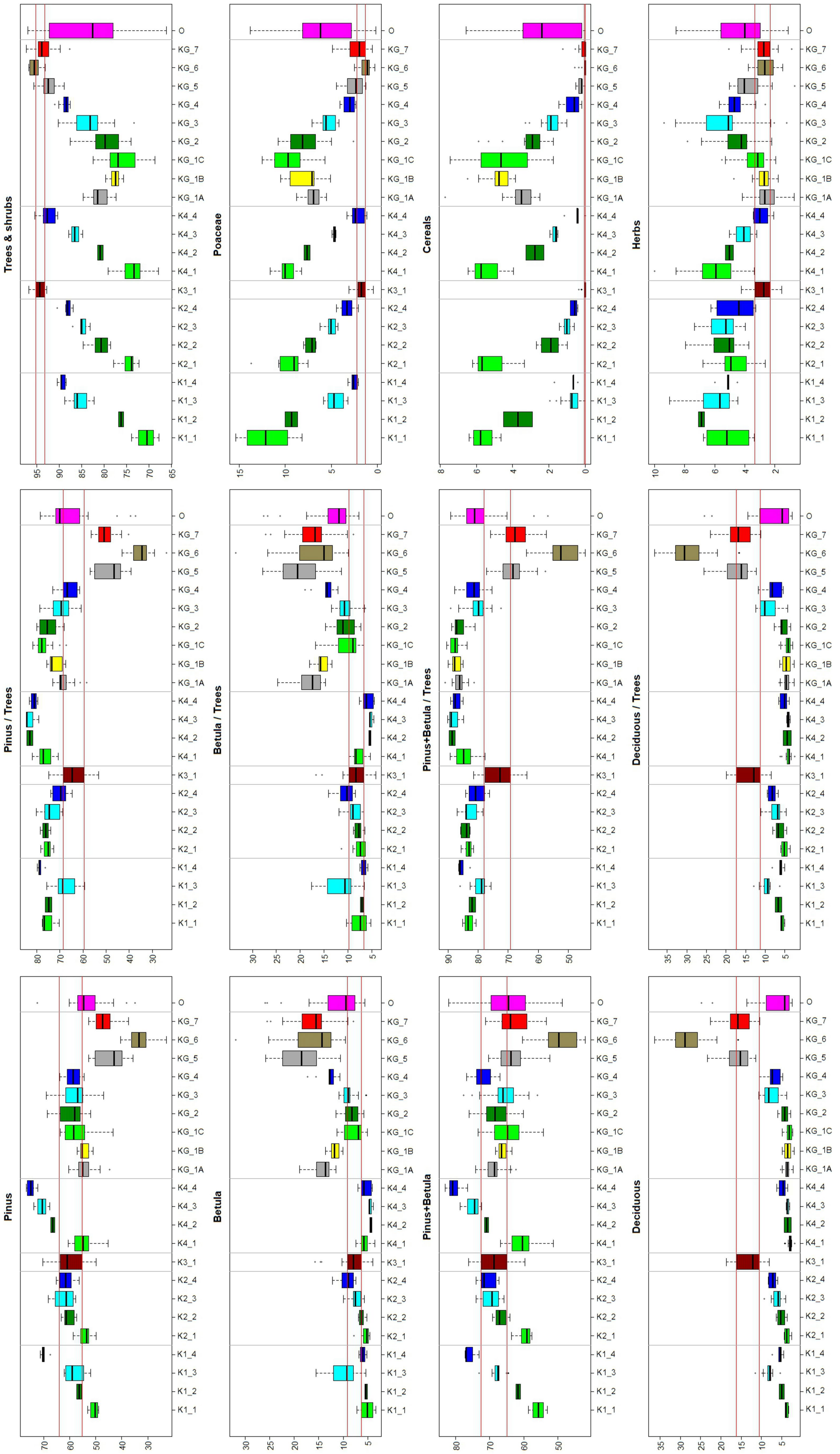

Figure 7. Comparison of ranges, quartiles and median values of littoral and deep core zones. Upper and lower dark-red horizontal lines encompass the boxes of the K-3_1 (6–20 cm) and K-3_2 (21–35 cm) zones. The last white boxplot on the right represents outlier samples. Names and colours of boxes correspond to those used in the tables in the text and in the palaeoecological diagrams

Visual comparison of selected pollen curves was employed in pollen analysis, e.g. Makohonienko (2000) matched cores from two lakes located close to each other by visual inspection of *Carpinus* and anthropogenic indicators curves. Väliranta et al. (2005) used shifts in the pollen proportions of *Betula*, *Pinus* and Ericaceae to validate the core chronology. David et al. (1998) used distinctive peaks and/or sustained increases/decreases in abundance in their pollen profiles as useful marker horizons for correlation. Pollen trends were also applied by Van der Knaap et al. (2000) for biostratigraphic correlation among pollen diagrams.

Since the 1970s, advances in computer technology have led to the widespread use of numerical methodologies in Quaternary palaeoecology (Gordon and Birks, 1974; see review in Thomson et al., 2012). Pels et al. (1996) provided an overview of biostratigraphic correlation methods and proposed their automation. Numerical approaches are less subjective than visual ones. One can decide whether to use the available stratigraphic information or omit it entirely. The first option leads to stratigraphically constrained analysis, which can be applied either as zone-by-zone comparison if zonation has already been done, or as sequence slotting (Birks and Gordon, 1985). Zone-by-zone comparisons, for instance, were introduced into the MultCor module of the POLPAL software (Walanus and Nalepka, 2006). The module uses the Manhattan metric as a measure of dissimilarity. This method was used by Drzymulska et al. (2014) to correlate shallow-water and deep-water cores based on differentiated pollen zones (littoral versus deep-water cores) in order to detect sedimentary gaps in the shallow-water cores.

In the analysed cores, the lack of zonation and the probable removal of sediments in the littoral cores precluded the use of methods based on zone comparison and stratigraphically constrained methods. The only option left was classification methods, which not only do not require zones to be specified but also allow them to emerge during analysis (Birks and Gordon, 1985). This was particularly important given the differing lengths of the analysed sequences (30 samples in the littoral cores versus 287 in the deep-water core). These methods are useful for comparing several different pollen diagrams (Birks and Gordon, 1985). They are complementary to data clustering, but unlike cluster analysis, ordination orders quantities in a lower-dimensional latent space, where similar samples are represented by points close together and dissimilar objects are farther apart.

Such an ordination of stratigraphic data and plotting the results in a two-dimensional space can provide a useful summary of the major patterns of samples (dis)similarity, whereas a stratigraphically constrained method with its concern for partitioning the sequence into homogeneous groups may obscure the detection of outlier samples (Birks, 1998). Samples that differ markedly from their neighbours are highlighted, and can be excised from potential local zones.

Because ordination methods use a distance function as their metric to position the objects with respect to one another in ordination space, it is important to ensure that the chosen distance is meaningful for the objects under study, but this is rather an ecological, not a statistical decision (Legendre and Birks, 2012). Analysing data containing many double-zero pairs requires not Euclidean but asymmetrical-type measure, which excludes double-zeros from the calculations. Because the most popular ordination method, PCA, has an internally built Euclidean distance, there was a need to employ an ordination method that allows the choice of a metric type. Principal Coordinate Analysis (PCoA, also called MDS, Multi-Dimensional Scaling) is a distance-based ordination technique that enables finding a set of Euclidean distances approximately equal to the dissimilarities representing a set of non-Euclidean distances (Gower, 1966). PCoA produces a set of orthogonal axes whose importance is measured by eigenvalues, as in PCA, and therefore has stronger interpretability than Non-metric MDS, another ordination technique often used in palaeoecology. Our data has many abundant and rare species, therefore Bray-Curtis dissimilarity, which equalises differences between abundant and rare species (Legendre and Legendre, 1998), was applied. The distance matrix was calculated directly on proportional pollen data, which is an equivalent to counting data transformed into profiles (vegan's library decostand 'total' method). The obtained results were very similar to those obtained using other coefficients for the analysis of quantitative assemblage composition data, such as chord distance or Hellinger distance (Legendre and Birks, 2012).

CONCLUSIONS

1. The presented chronological addendum to Milecka et al. (2021) documented sedimentary gaps in surface deposits, a much older age of littoral sediments than reported variable sedimentation rates among cores, and – in core K3 – the absence of deposits contemporaneous with those in other littoral cores.

2. According to the revised chronology, *Lobelia dortmanna* appeared in the lake no later than the sixteenth century, rather than at the beginning of the twentieth century.

3. The distinctiveness of surface samples was demonstrated. Consequently, the representativeness of pollen spectra recorded in shallow littoral sediments is relative, and their interpretation requires caution, because the different locations of the analysed cores within the basin have certainly created different depositional environments, affecting sediment composition and deposition.

4. A detailed chronology, potentially offered by isotopic dating, was not adequately established, as this method proved ineffective in the Lake Krzywce Wielkie case due to disturbance of the sedimentary environment. Although palynostratigraphic correlation is only tentative and uncertain in terms of chronology, it nevertheless enabled a reliable reconstruction of lake development.

5. Palynostratigraphic correlation is particularly useful for analysing the youngest sediments, where numerous anthropogenic taxa generate greater spectral diversity, aiding the assessment of pollen-spectrum similarity. Conversely, these youngest sediments from the last two centuries pose the greatest challenge for isotopic dating, especially given the randomness of plant remains to be dated and sediment mixing. The results also showed that palynostratigraphic correlation is relative, as LaPAZ-5 to LaPAZ-7 could not be separated due to insufficient differences in pollen spectra.

6. It is necessary to carefully assess the suitability of individual pollen spectra for correlation. Pollen deposition on the sediment surface is determined by multiple factors (Jacobson and Bradshaw, 1981), including wind, which can cause substantial concentration on the windward side. Therefore, particular caution is required when interpreting the variability of the most abundant taxa. In the analysed cores, spectra of *Pinus* – and especially *Betula* – virtually precluded core correlation.

7. Using ordination methods rather than clustering for pollen-zone delineation offers greater interpretative flexibility. Ordination highlights zones of change rather than strict boundaries. Points located close together on a biplot indicate the ‘core’ of a given zone, representing periods of minor change, while outlying points indicate transitional stages. Interpretation of biplots thus provides greater flexibility than grouping, primarily by avoiding rigid assignment to a specific cluster.

8. Although not widely used, the applied method may prove useful for more precise correlation of pollen diagrams from interglacial sediments.

ACKNOWLEDGEMENTS

Grateful acknowledgement is made to Professor Krystyna Milecka for kindly supplying the pollen data employed in this study.

ADDITIONAL INFORMATION

CONFLICT OF INTEREST. The authors have no conflicts of interest to declare.

ETHICAL STATEMENT. The authors have no ethical statement to make.

FUNDING. None.

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