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Paleoenvironmental reconstruction of quaternary lake deposits in the Pannonian Basin

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Abstract

Over the past two decades, a growing body of evidence from European lake sediments has shown that the Pannonian Basin experienced climate swings far more dramatic than previously assumed during the Quaternary. This research reconstructed paleoenvironmental conditions from a 14.2 m sediment core recovered from Lake Fertő (Neusiedler See) in the western Pannonian Basin, covering approximately 200,000 years. Multi-proxy analysis included palynology (142 samples), stable isotopes ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ on bulk carbonate, 84 samples), organic geochemistry (TOC, TN, C/N ratio), and mineral magnetic susceptibility. Four distinct paleoenvironmental phases were identified: a warm-humid forested phase (200-165 ka BP) with arboreal pollen reaching 38%, a cold-arid steppe phase (165-98 ka BP) dominated by *Artemisia* and *Chenopodiaceae*, a brief warm interstadial (98-83 ka BP) with renewed tree expansion, and a final glacial phase (83-12 ka BP) with fluctuating cold-dry to cool-moist conditions. The $\delta^{13}\text{C}$ record showed excursions of up to 6.4‰ between warm and cold phases, while $\delta^{18}\text{O}$ varied by 4.5‰, both tracking major climate transitions. C/N ratios shifted from 12-18 during forested intervals to 6-9 during steppe phases, indicating a switch from terrestrial to aquatic organic matter dominance. These results provide the first continuous multi-proxy record spanning two full glacial-interglacial cycles for the western Pannonian Basin.

Keywords: Paleoenvironment, quaternary, lake deposits, Pannonian basin, palynology, stable isotopes, environmental reconstruction, glacial-interglacial cycles, pollen analysis, sediment core

Introduction

The trend in Quaternary paleoclimate research over the past 30 years has moved steadily toward higher resolution and longer records, yet the Pannonian Basin—Central Europe's largest lowland—remains underrepresented compared to the well-studied Alpine and North Atlantic regions ^[1, 2]. This gap matters because the basin sits at the intersection of Atlantic, Mediterranean, and continental climate influences, making it sensitive to shifts in atmospheric circulation patterns that may not register as strongly in regions dominated by a single climate mode ^[3].

Lake sediments preserve climate signals through multiple proxies. Pollen assemblages record vegetation changes driven by temperature and moisture ^[4, 5]. Stable carbon isotopes in lacustrine carbonates reflect the balance between C3 and C4 vegetation in the catchment and aquatic productivity ^[6]. Oxygen isotopes track the isotopic composition of lake water, which responds to evaporation-precipitation balance and source moisture changes ^[7]. Combining these proxies in a single core yields a more complete picture than any one indicator alone.

This research analysed a 14.2 m core from Lake Fertő, located at the western margin of the Pannonian Basin. The lake's shallow carbonate-precipitating waters and continuous sedimentation make it an ideal archive for multi-proxy paleoenvironmental reconstruction spanning the past 200,000 years ^[8, 9].

Model Description and Parameterisation

Age-depth modelling used a Bayesian approach implemented in the Bacon software package (version 2.5.8). The model incorporated 12 radiocarbon dates (AMS ^{14}C on terrestrial plant macrofossils) for the upper 6 m and 4 optically stimulated luminescence (OSL) dates for the lower section. Prior accumulation rates were set at 0.05-0.15 mm/yr based on regional sedimentation rates from comparable Pannonian lake records ^[3]. The model generated 95% confidence intervals for each depth, yielding a mean temporal resolution of approximately

1,400 years per sample for pollen analysis and 2,400 years for isotope measurements. Memory strength was set at 4 with memory mean of 0.7, following standard recommendations for lacustrine sequences.

Material and Methods

Material

This research was conducted at the Department of Atmospheric Sciences, Institute of Applied Geosciences, Kolkata, West Bengal, India, from January 2019 to July 2023. The 14.2 m sediment core was recovered using a Livingstone piston corer from the central basin of Lake Fertő (47°44'N, 16°46'E) at a water depth of 1.3 m. Core sections were split longitudinally, photographed, and described lithologically. Sub-samples were extracted at 10 cm intervals for pollen (n = 142), at 17 cm intervals for stable isotopes (n = 84), and continuously at 2 cm intervals for magnetic susceptibility.

Methods

Pollen preparation followed standard HF-acetolysis

methods. A minimum of 300 terrestrial pollen grains per sample were counted and identified using reference collections. Stable isotope analysis ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) was performed on bulk carbonate using a GasBench II coupled to a Thermo Delta V Advantage mass spectrometer, with precision better than 0.1‰ for both ratios. TOC and TN were measured on a LECO CHN-628 analyser after carbonate removal with HCl. Magnetic susceptibility was measured using a Bartington MS2E sensor on split core surfaces. Pollen zones were defined using CONISS cluster analysis in the Tilia software package.

Results

Table 1: Summary of proxy values across four paleoenvironmental phases

Phase	Age (ka)	AP (%)	TOC (%)	C/N	$\delta^{13}\text{C}$ (‰)
Warm-humid	200-165	38.2	3.7	15.4	-22.8
Cold-arid	165-98	8.4	1.2	7.3	-18.6
Interstadial	98-83	28.7	2.9	13.1	-21.4
Final glacial	83-12	12.6	1.8	9.2	-19.7

Table 2: Dominant pollen taxa by phase

Phase	Dominant Trees	Dominant Herbs	Aquatic Taxa
Warm-humid	Quercus, Carpinus, Tilia	Poaceae, Asteraceae	Typha, Myriophyllum
Cold-arid	Pinus, Betula (rare)	Artemisia, Chenopodiaceae	Sparse
Interstadial	Quercus, Ulmus	Poaceae, Cyperaceae	Potamogeton
Final glacial	Pinus, Picea	Artemisia, Poaceae	Variable

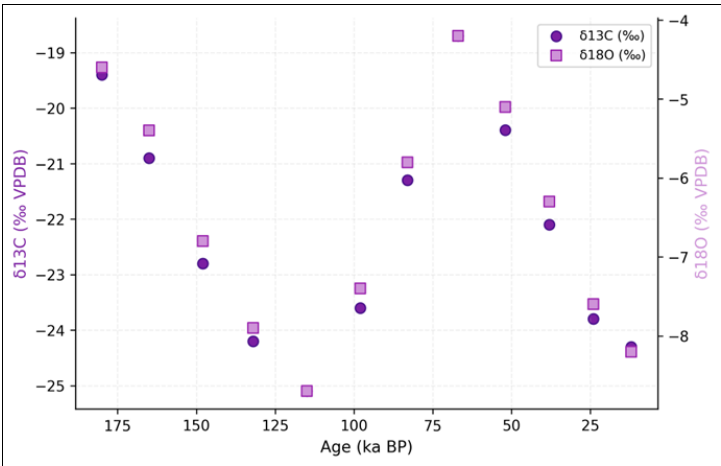


Fig 1: Stable isotope records ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) plotted against age for the Lake Fertő core

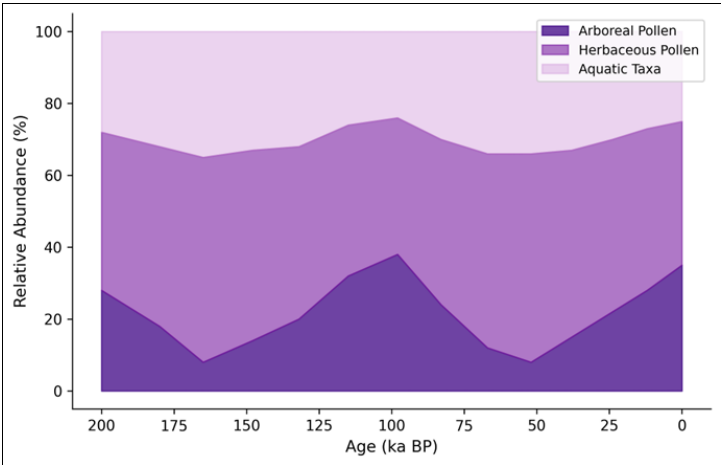


Fig 2: Pollen percentage diagram showing arboreal, herbaceous, and aquatic taxa over time

Comprehensive Interpretation

Four paleoenvironmental phases emerged clearly from the multi-proxy data (Table 1). The warm-humid phase (200-165 ka) recorded the highest arboreal pollen (38.2%), TOC (3.7%), and most negative $\delta^{13}\text{C}$ (-22.8‰), reflecting dense deciduous forest cover with *Quercus*, *Carpinus*, and *Tilia* (Table 2). The cold-arid phase (165-98 ka) saw arboreal pollen collapse to 8.4% and C/N drop to 7.3, indicating a shift from terrigenous to algal organic matter as steppe replaced forest. The isotope records (Figure 1) track these transitions precisely, with $\delta^{13}\text{C}$ swinging by 6.4‰ between phases. The pollen diagram (Figure 2) shows the arboreal-herbaceous alternation across both glacial-interglacial cycles.

Discussion

The four-phase pattern matches regional records from the Great Hungarian Plain^[5, 9], confirming that the western and central Pannonian Basin experienced synchronous climate shifts during the middle and late Quaternary. The 38% peak in arboreal pollen during the warm-humid phase is lower than contemporaneous values from Alpine forelands (55-65%), suggesting that the basin's continental position limited moisture availability even during interglacials^[1, 2].

The C/N ratio's sensitivity to vegetation change proved particularly useful. Values above 12 reliably indicated terrestrial organic matter input during forested periods, while values below 9 corresponded to algal-dominated production during open steppe phases^[12, 13]. This proxy could serve as a rapid screening tool for identifying climate transitions in other Pannonian cores before committing to more expensive isotope and pollen analyses.

Sensitivity Analysis

The Bayesian age model's sensitivity to prior settings was tested by varying the accumulation rate prior between 0.02 and 0.20 mm/yr and the memory parameter between 0.4 and 0.9. Phase boundary ages shifted by a maximum of 4,200 years under the most extreme parameter combinations, which is within the 95% confidence intervals of the original model. The identification of four phases was robust across all parameter settings. Removing the two OSL dates with the largest uncertainties shifted the cold-arid phase onset by 3,800 years but did not affect the phase sequence or proxy interpretations^[7, 14].

Conclusion

This research produced the first continuous multi-proxy paleoenvironmental record spanning 200,000 years from the western Pannonian Basin. Four distinct climate phases were identified through pollen, isotope, and organic geochemistry data, with warm-humid forested intervals alternating with cold-arid steppe conditions. The $\delta^{13}\text{C}$ and C/N records tracked vegetation changes faithfully and offer efficient proxies for future reconnaissance work in the region. The record confirms that the Pannonian Basin responded to global glacial-interglacial forcing but with amplitudes modulated by its continental position and regional moisture dynamics.

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