Doctoral School of Geosciences

Sedimentary records of abandoned channel alluviation: insights from compositional data analysis, endmember modeling, and wavelet transform.

Ph.D. Thesis

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1. INTRODUCTION

Meandering channels are common in the Quaternary River system. In this system, abandoned channels represent distinctive meandering sub-environments. "*Resulting from a series of processes, starting with cutoff initiation, followed by plug bar formation, and ultimately leading to the disconnection of the channel."* A comprehensive grasp of the sedimentary processes of abandoned channels is substantial in comprehending the Quaternary fluvial systems.

Grain size distribution (GSD) provides insights into transport and depositional processes within abandoned channels. The log-normal distribution is commonly used to quantify GSDs, in conjunction with tools like the probability density function (PDF). However, it is important to note that while log-normal distribution coefficients offer consistent results for distinct polymodal GSDs, this approach may not be appropriate as GSDs often deviate from log-normal patterns. The use of a PDF could potentially obscure significant variations within GSDs.

The issues posed by PDF can be addressed by applying multivariate statistics e.g., principal component analysis (PCA) and cluster analysis (CA). Nonetheless, due to the inherent compositional constraint, *"the sum of percentage contributions from individual size fractions is equal to 100%, therefore maintaining a closed system"* GSDs capture relative information on the entire distribution, necessitating a preliminary mathematical treatment.

By combining a compositional data analysis (CoDA) approach with PCA and CA, it becomes possible to analyze the entire GSD, a feat not achievable using PDF methods alone. Additionally, the variation in composition within a sediment sample can be explained by a combination of fixed compositions known as endmembers (EMs), each representing a distinct size fraction resulting from the same transport and depositional processes. Endmember modeling (EMM) is utilized to assess the proportional contributions of these EMs to compositional data, effectively separating a robust polymodal grain-size population. Moreover, obtaining a thorough understanding of evolution necessitates a quantitative spatial and temporal evaluation of the vertical sedimentation patterns.

This thesis presents a comprehensive geostatistical approach to characterize grain size distribution (GSD). The Quaternary sediments from Tövises in the eastern Great Hungarian Plain (Figure 1) are significant in the context of the study because they provide

valuable information about the sedimentation processes in oxbow lakes. The GSD of these sediments can be analyzed to understand the depositional processes. The study applies CoDA and multivariate statistics i.e. principal component analysis, cluster analysis, and discriminant analysis, to interpret the sedimentation processes in the Tövises bed. These approaches provide statistically significant and sedimentologically interpretable results, contributing to a better understanding of the sedimentation history in the region. Moreover, the adequate explanation of the wavelet decomposition and Morlet scalogram helped identify the thickness, depth, and level of significant high-energy depositional events.

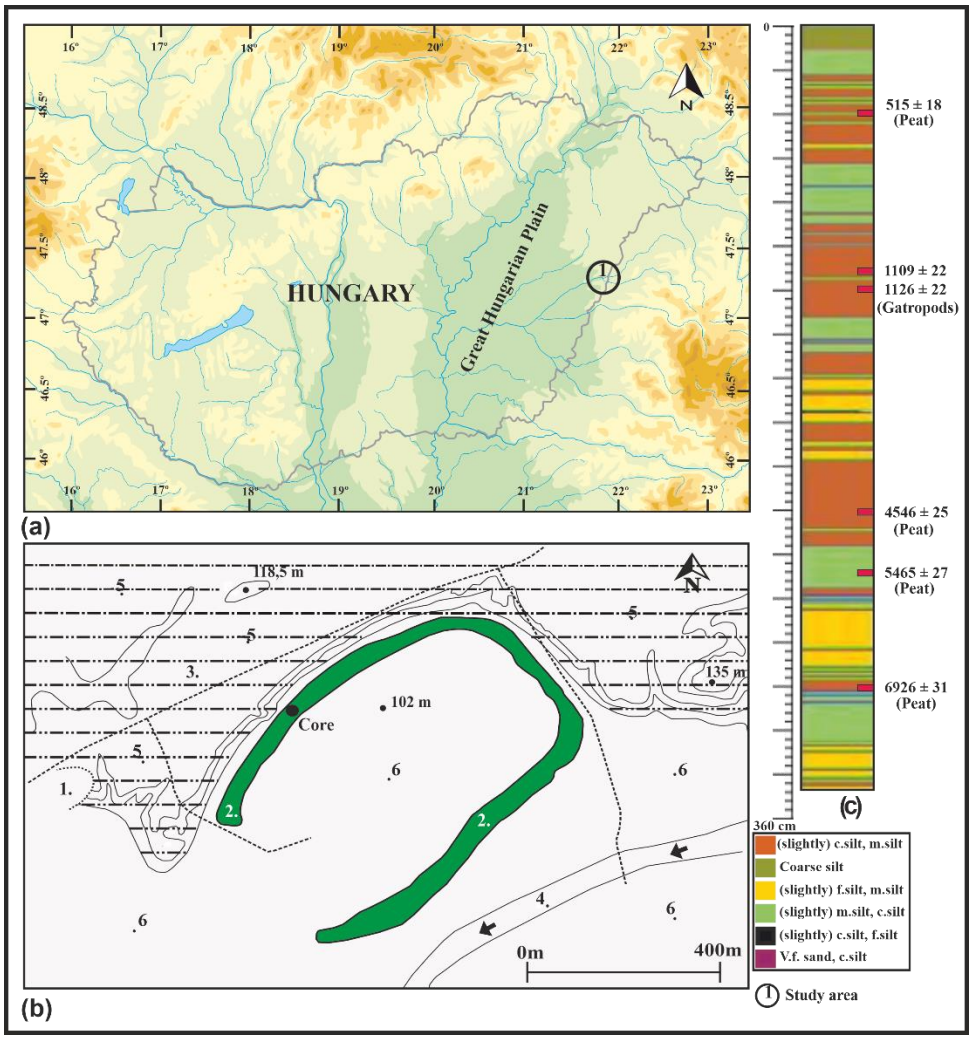

Figure .1 Map of the study area. (a) Location of the Tövises paleochannel; (b) the core location and geology of the vicinity: 1. sandpit, 2. Tövises paleochannel, 3. loess-covered Pleistocene alluvial fan, 4. canalized bed of Ér creek, 5. loess, and 6. alluvia sediments; (c) Lithology and the chronology of the core sediments.

2. DATA AND METHODOLOGY

The dataset is multiproxy data; it contains different measurements of sediments retrieved from the Tövises bed abandoned channel. The ^{14}C ages of six samples, covering the period from circa 515 ± 18 to 6926 ± 3, the 2σ calibrated ages, and the weighted mean age ranging from circa 532 to 7748 cal yr before present (BP) (Table 1). The raw GSDs of 345 samples with grain sizes ranging from 0.1 – 500 μm. The grain size range of each sample was plotted against it is fractional abundance which showed polymodal distributions of six sub-modes ranging from 2.5 to 11 ϕ (Figure 2).

Table 1. AMS radiocarbon dates for samples from Tövises bed core.

Lab ID	Depth (cm)	Sample Type	Conventional ^{14}C Age	Calibrated ^{14}C Age (2σ BP)	Weighted Mean ^{14}C Age (BP)
DeA-29986	43	Peat "bulk"	515 ± 18	514–545	532 ± 15.5
DeA-29550	116	*P.corneus* shell	1109 ± 22	958–1058	1007 ± 50
DeA-29551	121	*P.corneus* shell	1126 ± 22	959–1065	1016 ± 53
DeA-29988	224	Peat "bulk"	4546 ± 25	5052–5188	5161 ± 68
DeA-29990	252	Peat "bulk"	5465 ± 27	6266–6305	6273 ± 19.5
DeA-29992	305	Peat "bulk"	6926 ± 31	7678–7799	7748 ± 60.5

The chronology of the sediment was established using radiocarbon dating; the age-depth model was constructed using Bayesian statistics, implemented in the R bacon package. Loss-on-ignition (LOI) measurements involved heating samples to quantify organic material and carbonate content. Magnetic susceptibility (MS) was measured to reveal the changes in magnetic mineral composition that can be linked to climatic conditions.

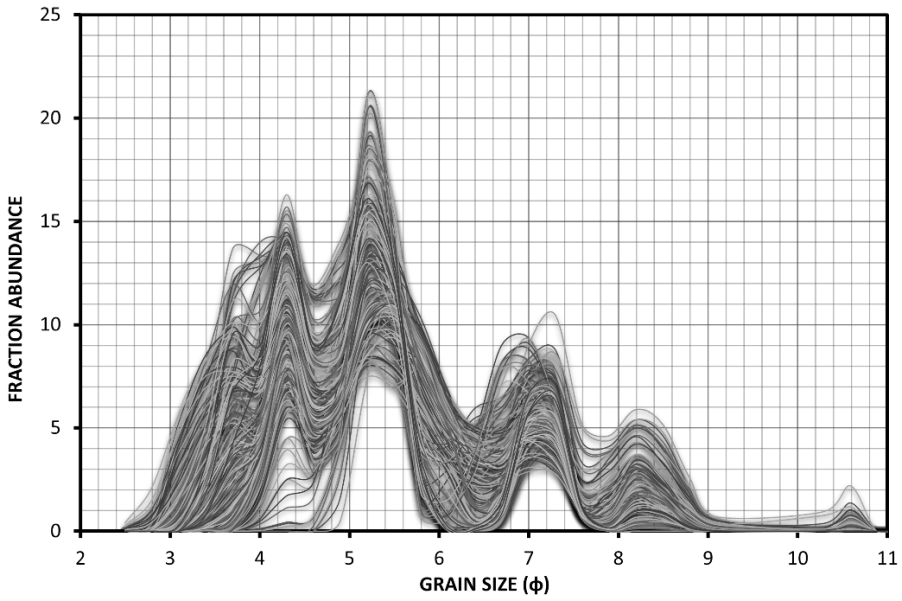

Figure 2. GSD characteristics of the Tövises bed core. (a) Overlay plot of the GSDs of the 345 samples, illustrating the polymodality of Tövises bed sediments.

PCA effectively reduces the dimensionality of the GSD while preserving important information. It detects principal components that capture variations in grain size parameters. To unveil diverse sediment transport and depositional modes, hierarchical clustering was utilized. For each group, discriminant analysis (DA) facilitates the categorization of both observed and new cases; clusters with greater standardized coefficients are significant in distinguishing between groups. The CM diagram helped interpret the depositional processes of the clusters. It uses cumulative GSD median and percentiles to represent sediment characteristics, aiding in the interpretation of sedimentary processes.

EMM deconstructs complex sediment composition variations into distinct endmembers. This approach helped reveal the underlying sedimentation processes by identifying unique grain size modes associated with different transport and deposition histories.

The application of WT in quantifying the related patterns of transport and deposition processes, providing a suitable mathematical representation of the alluviation history of the abandoned channel. Wavelet transform (WT) examined the cyclical patterns in coarser grain size fractions, it helped capture the local and temporal information, enabling the detection of gradual and abrupt variations in grain size over different scales.

3. RESULTS AND CONCLUSIONS

3.1 Compositional data analysis (CoDA) and multivariate statistics

PCA applied to data clr-transformed data yielded two components, accounting for ~ 83% of the total variance. The PC_1 explained ~60 % of the variance, the PC_2 explained ~23% (Figure 3a). The clay to medium silt exhibited positive loadings, while the coarsest size fractions displayed negative loadings (Figure 3b). Notably, variations in the M and C parameters aligned with changes in the coarse silt fraction in PC_2.

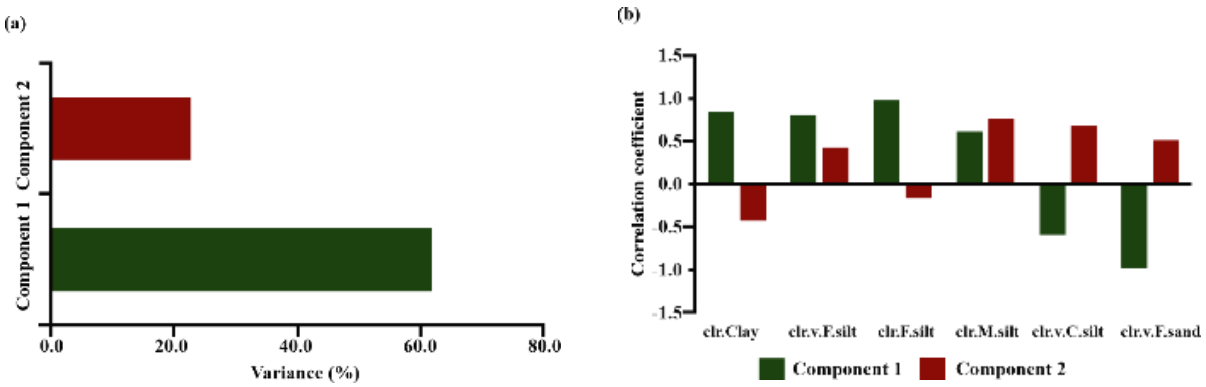

Figure 3. a. Scree plot of the variance (%) explained by the first and second principal components (PC1 and PC2). b Correlation coefficients (loadings) of the PC1 and PC2 of the grain size fractions

CA was employed on the principal component scores and identified four groups. The classification's statistical validity is confirmed by the DA, which showed a high ~ 95% percent correct. The effectiveness of clustering was gauged using sedimentological criteria, exemplified by the CM diagram (Figure 4). Accordingly, the depositional process involved both uniform suspension (SR in Figures 4 and 53) and graded suspension (RQ in Figures 4 and 5). Within the graded suspension section (section RS), three parts are discernible: fine-grained, medium-grained, and coarse-grained graded suspension. The clustering could not create a clear demarcation between graded suspensions (QR) and uniform suspension (RS) (Figure 4). Cluster 4 represents both uniform and graded suspension depositions. However, this approach is suitable in scenarios where sedimentological criteria serve as effective validation tests.

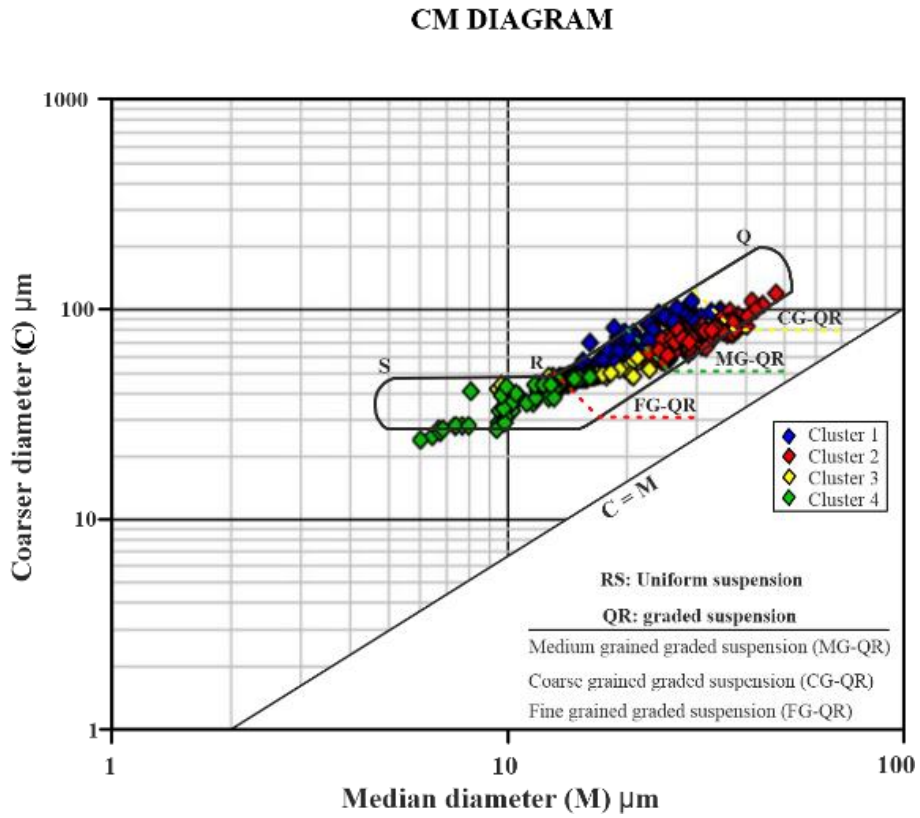

Figure 4. The CM diagram illustrating the of the clucluster'soups (Passega 1964).

The results indicated that the deposition took place in a series of stages, with uniform and graded suspension loads (Figure 5). These stages were occasionally interrupted by bottom current loads. In the context of CoDA, these stages exhibited patterns of coarsening-upward sequences, suggesting regular deposition. These findings represent promising prospects for employing CoDA, coupled with PCA and CA, in the analysis of sedimentation mechanisms of the abandoned channel sediments, yielding satisfactory statistical significance and geological insights. Nevertheless, the dependability of this method should be verified through comparison with sedimentological and geological benchmarks, given its intermittent capability to yield substantial outcomes.

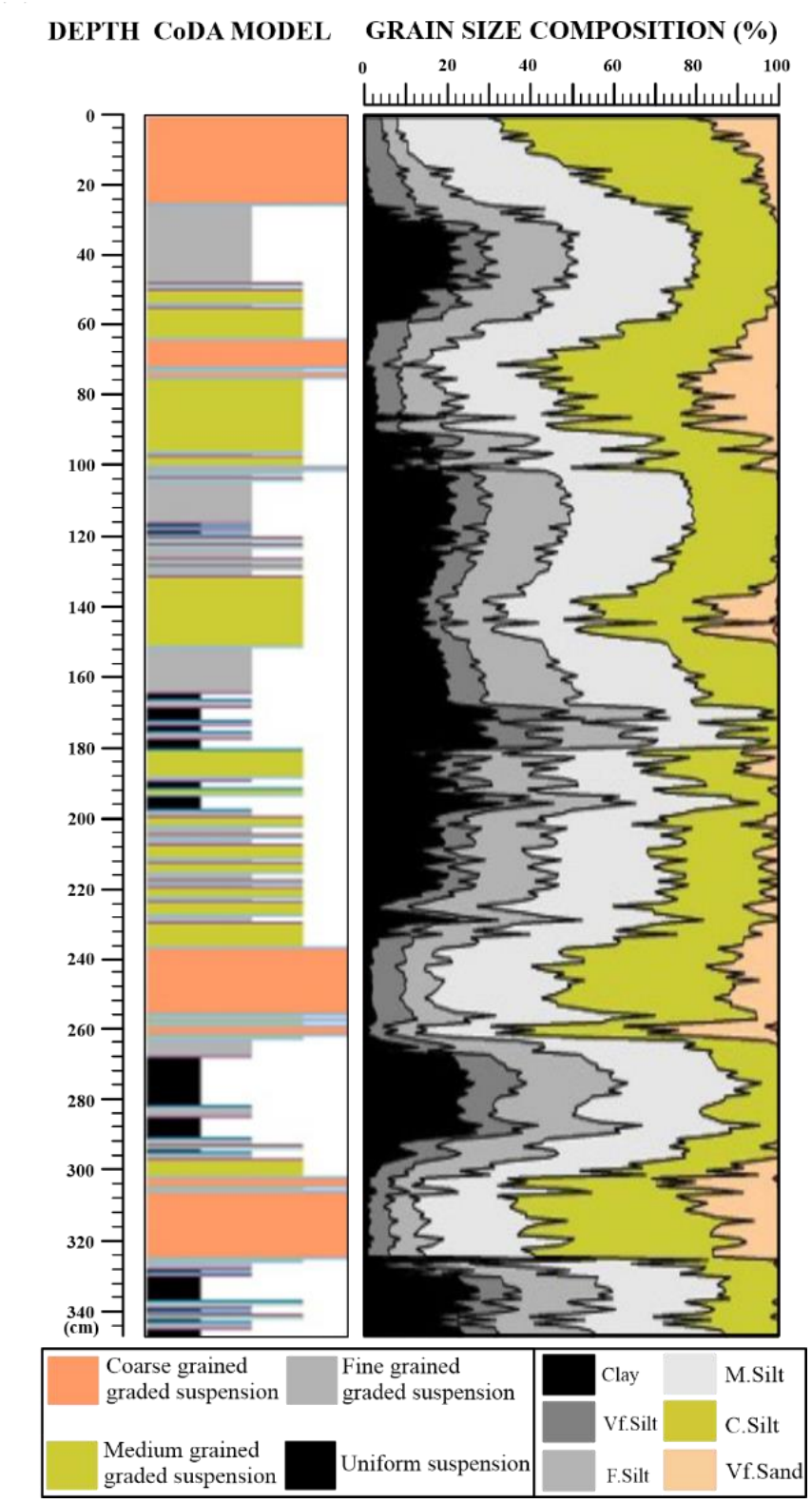

Figure 5. The vertical relations of the depositional processes depositional model constructed based on CoDA as drawn from the CM diagram.

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3.2 Grain-Size Endmember Modeling (EMM)

Sediments analyzed using EMM, revealed four EMs (Figure 6). The four EMs model demonstrated optimization with 94% of the variance.

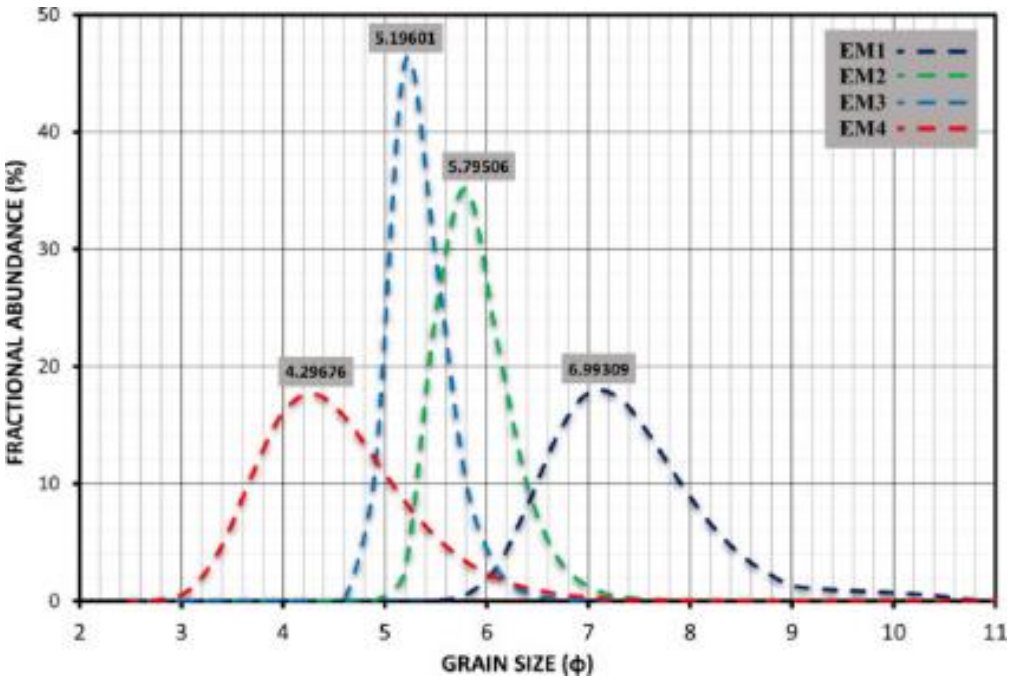

Figure 6. Representation of the four endmembers (EMs) resulting from the statistical unmixing of the original grain size distribution (GSDs).

EM1 is moderate to well-sorted fine silt, EM2 and EM3 are well to very well-sorted coarse to fine silt, and EM4 is moderately sorted fine sand to medium silt. The proportional

contributions of the EMs are 26.43% (EM1), 12.21% (EM2), 18.90% (EM3), and 42.46% (EM4).

The positive correlation between Mz and EM4 suggests that EM4 can suggest low to moderate depositional energy. EM1 content is consistent across Oxbow Lake infill units (OL1–OL5), higher than overbank units (OB1–OB5). EM2 and EM3 content fluctuates in all units, with similarity in OL2 and OL5, and presence in OB4 and OB5. EM4 is present in all units, higher in overbank than oxbow lake infill units. LOI records display shifts in organic content during oxbow filling phases. MS values vary, showing peaks and fluctuations, aligned with sediment grain size trends. The higher MS range has notable peaks around 3000-400 BP and 1700-1000 BP.

The analysis of the dataset indicates the Tövises bed paleochannel evolved during the mid to late Holocene. This evolution involved the lake gradually filling in with lacustrine gyttjas and interbedded wetland histosol, along with periodic flood deposits. Changes in climate across Europe, with wet and dry periods, are reflected in the organic-rich beds and peat sediments. EM1 consists of fine sediments within the oxbow lake, while EM2 and EM3 primarily contain silt deposited during moderate flooding events. EM4, the coarsest component, represents sediments transported during significant floods, particularly through overbank flow.

Magnetic susceptibility (MS) data suggested wet and reducing conditions followed by drier periods resembling lacustrine cycles, with iron minerals indicating wet conditions. The coarse sediment component (EM4) of the sediments correlates with both flood events and climatic fluctuations. Comparing this component with records of oxygen isotopes, annual precipitation, and mean annual precipitation over time reveals patterns of warm and cold events throughout the Holocene.

3.3 Wavelet transform and sedimentary cyclicity.

The continuous wavelet transforms (CWT) applied to the sand fraction (Figure 7) revealed periodic patterns at small, medium, and large scales. WT identified the intensity and the recurrence of these transport and depositional processes. The large-scale cycles depicted the general trend of the sedimentation processes and environmental conditions. In contrast, the medium-scale (i.e., intense ~ 22.4, 10, and 8 cm cycles between circa 7 and 6 ka yrs BP and weaker ~ 10 and 8 cm cycles between circa 4–2 ka yrs BP) (Figure 7a) and small-

scale cycles (i.e., ~ 4.5 and 2.8 cm at the bottom of the sequence during the circa 8 -7.5 Ka yrs BP and ~ 4.8 cm at the top of the sequence between circa 2.5–2 ka yrs BP) (Figure 7b) may reflect the local variability of the transport energy.

Comparing these cycles with the CoDA model and EMM, it is indicated that cycles can be related to higher energy conditions of different magnitudes. Significant floods occurred at the bottom of the sequence between circa 7–6 ka yrs BP, while moderate flood events can be seen at the top of the sequence during circa 3.5 ka yrs BP; how the middle of the sequence between circa 6–4 ka years BP witnessed week flood events.

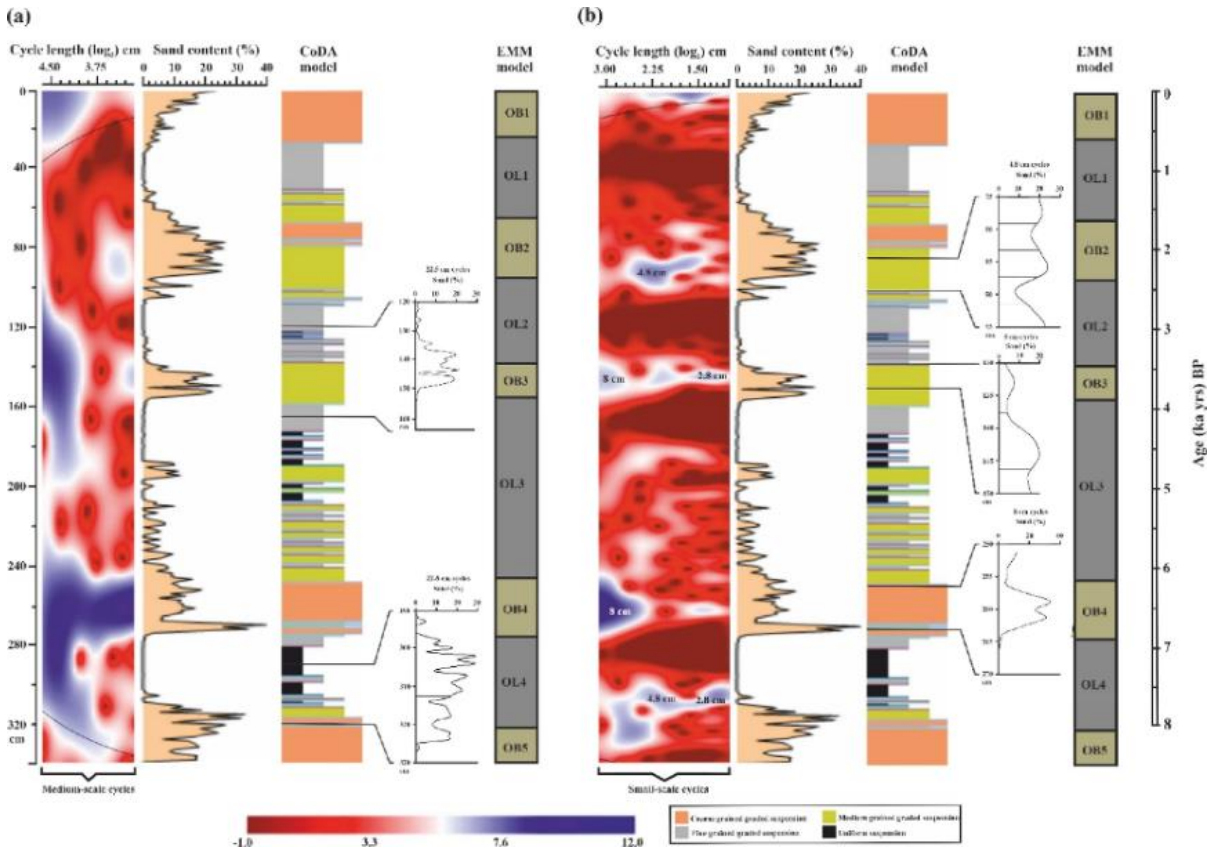

Figure 7. Represents the medium and small-scale cycles of sand content with their Morlet representation and its scalograms at different scales, average power spectrum, and significance intervals. a Represent the medium-scale cycles of (~ 4.8 cm) and detailed cyclicity. b Represents the small-scale cycles of (~ 4.8 and 2.8 cm). The notions OB1-5 and OL1-4 in the endmember (EMM) model are overbank and oxbow lake intervals respectively.

The research presented aimed to enhance our understanding of past environmental conditions and deposition processes by utilizing grain size distribution (GSD) analysis in conjunction with advanced statistical techniques; (CoDA), endmember modeling (EMM), and wavelet transformation (WT). These techniques offered a more comprehensive insight into the abandoned channel alluviation process by considering the entire GSD in spatial and temporal domains.

The centered log-ratio transformation, and multivariate methods proved instrumental in scrutinizing GSDs. PCA identified sedimentation mechanisms impacting distinct grain sizes, CA differentiated suspension types linked to channel-main system connections, and DA validated these clusters, offering insights into depositional processes and environmental shifts. The results suggested that CoDA yield valuable insights into the sedimentation history, identifying depositional processes linked to grain size variations.

Endmember modeling, combined with magnetic susceptibility (MS) and loss-on-ignition (LOI) analyses, contributed to a comprehensive understanding of sedimentological processes, paleoenvironmental changes, and climatic variations over the ~ 8000 BP. Four distinct endmembers representing different grain sizes help characterize deposition conditions and provide insights into changing river dynamics. MS and LOI analyses support these findings by indicating wet and dry conditions and fluctuations in organic content.

Wavelet transform (WT) is employed to analyze cyclicity in depositional processes, capturing both short and long-term cycles. The results revealed quasi-periodic cyclicities in sand content data, reflecting both external factors like floods and internal processes like channel dynamics.

In conclusion, the integration of CoDA, PCA, CA, and WT to analyze GSD from an abandoned channel offers a statistically significant and geologically interpretable model of sedimentation processes. The study highlights distinct depositional mechanisms and provides insights into cyclic patterns driven by both external and internal factors, contributing to our understanding of the history of sedimentation in abandoned channels and Quaternary fluvial systems.

List of publications used in the thesis.

Abdelrhim Eltijani (MTMT author ID: 10070432)

Eltijani, A., Molnár, D., & Geiger, J. (2023). Characterizing Sedimentary Processes in Abandoned Channel using Compositional Data Analysis and Wavelet Transform. Int J Geomath 14, 11 (2023). https://doi.org/10.1007/s13137-023-00223-y

Eltijani, A., Molnár, D., Makó, L., Geiger, J., & Sümegi, P. (2022). Application of Parameterized Grain-Size Endmember Modeling in the Study of Quaternary Oxbow Lake Sedimentation: A Case Study of Tövises Bed Sediments in the Eastern Great Hungarian Plain. Quaternary, 5(4),44. https://doi.org/10.3390/quat5040044

Eltijani, A., Molnár, D., Makó, L., Geiger, J., & Sümegi, P. (2022). Applying Grain-Size and Compositional Data Analysis for Interpretation of The Quaternary Oxbow Lake Sedimentation Processes: Great Hungarian Plain. 39(2). https://doi.org/10.24425/sq.2022.140885

Other publications

Eltijani, A., Molnár, D., & Geiger, J. (2023). Paleoenvironmental multiproxy dataset of the Quaternary abandoned channel in Tövises bed, Great Hungarian Plain, Data in Brief, 49, https://doi.org/10.1016/j.dib.2023.109344

Mohammed, M.A.A., **Eltijani, A.**, Szabó, N.P. et al. Hydro-chemometrics of the Nubian Aquifer in Sudan: an integration of groundwater quality index, multivariate statistics, and human health risk assessment. Discover Water 3, 15 (2023). https://doi.org/10.1007/s43832-023-00039-9

Conferences abstracts

International Congress on Geomathematics in Earth- & Environmental Sciences, and the 22nd Hungarian Geomathematical Congress. 2022, Pecs, Hungary.

International Congress on Geomathematics in Earth- & Environmental Sciences, and the 22nd Hungarian Geomathematical Congress. 2021, Budapest, Hungary.