Geostatistical modeling of sediment series geometry and integration of seismic, sedimentological, and eustatic data for paleogeographic reconstructions

Abstract of the doctoral dissertation:

The shoreline and the continental shelf are subject to continuous morphological transformations resulting from a range of natural factors: global sea-level changes; horizontal and vertical litosphere movements; sediment dynamics, which include erosion, accumulation, redeposition, and compaction processes; as well as changes induced by human activity. Due to the complexity of this system, the generation of geometric models of sedimentary series and paleogeographic models requires extensive and comprehensive research, including sedimentological analyses, interpretation of geophysical data, synthesis of diverse geological information from multiple sources, and spatial modelling (interpolation and extrapolation) of data using geostatistical tools. Paleogeographic reconstruction for different areas requires the application of consistent methodology while simultaneously considering regional and local setting. Examples of geometric modelling of sedimentary series developed from this perspective are presented in the three original scientific articles that constitute this dissertation:

1. **Miluch, J.**, Osadczuk, A., Feldens, P., Harff, J., Maciąg, Ł., Chen, H., 2021: Seismic profiling-based modeling of geometry and sedimentary architecture of the Late Pleistocene delta in the Beibu Gulf, SW of Hainan Island (South China Sea). *Journal of Asian Earth Sciences*, 205, 104611, https://doi.org/10.1016/j.jseaes.2020.104611
2. **Miluch, J.**, Maciąg, Ł., Osadczuk, A., Harff, J., Jiang, T., Chen, H., Borówka, R.K., McCartney, K., 2022: Multivariate geostatistical modeling of seismic data: Case study of the Late Pleistocene paleodelta architecture (SW off-shore Hainan Island, South China Sea). *Marine and Petroleum Geology*, 136, 105467, https://doi.org/10.1016/j.marpetgeo.2021.105467
3. **Miluch, J.**, Zhang, W., Harff, J., Groh, A., Arlinghaus, P., Denker, C., 2025: Paleogeographic numerical modelling of marginal seas for the Holocene - an exemplary study of the Baltic Sea, Earth System Dynamics, 16(2), 585-605, https://doi.org/10.5194/esd-16-585-2025

The first of the three articles submitted for review focused on the analysis of seismic data from the South China Sea in order to model the geometry of a paleodelta discovered on the continental shelf southwestern of Hainan Island during an initial assessment of the collected

geophysical data[1]. Discovery of the layer containing characteristic deltaic clinoforms served as the starting point for launching the Polish–Chinese research project " Evolution of the Hainan delta as a response to changes in palaeoenvironment since late Pleistocene (ERES)", within which the candidate was responsible for interpreting geophysical data and conducting sedimentological analyses. In the analysed seismic profiles, the R1 and R2 reflectors, corresponding to erosional surfaces forming the top and bottom of the deltaic deposits were distinguished; their ages, based on OSL dating, were determined as 56 kyr BP and 65 kyr BP, respectively. Geostatistical interpolation tools were then applied to model the top and bottom surfaces and to generate thickness models of both the deltaic and post-deltaic series. Modeling was supported by lithological data from the 100 meter long ZBW sediment core, which enabled the determination of sound volocity in individual units. Plotting the points where erosional incisions were identified on the seismic profiles onto the modelled surfaces allowed the reconstruction of two generations of distributary channel systems. Analysis of the apparent dip angles of deltaic clinoforms at profile intersection points made it possible to calculate true dips and true azimuths, thereby confirming the hypothesis that the sediments forming the paleodelta originated from Hainan Island. Based on the thickness model, sediment parameters, and available OSL dating results, it was possible to estimate the volume and mass of the sediments building the paleodelta and to calculate an annual sediment supply of $282 \pm 20 \times 10^6$ t/yr. Deposition of such a large volume of sediment may have resulted from intense weathering of the rocks forming Hainan Island, likely driven by extreme climatic conditions, sea-level fluctuations, and tectonic uplift of the island. This publication formed part of a comprehensive study of the "Hainan Delta," which represents a potential paleoclimate research „hot spot" for the Last Glacial Period. Furthermore, it was concluded that the paleodelta in Beibu Gulf, along with the associated coastal and terrestrial areas, may serve as an ideal region for source-to-sink studies addressing climate dynamics in the context of extreme climatic events and geohazards.

The second article focuses on the methodological aspect of geometric modelling of paleodelta deposits, which involved selecting the most optimal model parameters for interpolation using the kriging method. The modelling trials involved a spherical model and a nested Gaussian–power model, both of which additionally accounted for the nugget effect. Multiple interpolations of the same dataset using variable parameters, combined with cross-validation of the results, demonstrated that the most optimal method for interpolating the

[1] Chen, H., Harff, J., Qiu, Y., Osadczuk, A., Zhang, J., Tomczak, M., Cui, Z., Cai, G., 2015. Last Glacial Cycle and Seismic Stratigraphic Sequences at the West Offshore of Hainan Island, Northwestern of the South China Sea. Spec. Publ. Ser., Geol. Soc. Lond. 429, 99–121. https://doi.org/10.1144/SP429.9

seismic data was the nested model with a minimal nugget effect. Although the modelled values exhibited slightly poorer “fit” in the immediate vicinity of the profiles, the kriging variance in the areas between the profiles was significantly lower than in the case of the more commonly used spherical model. The study also examined the influence of the adopted methodology—both in terms of the kriging model and the grid resolution—on the variance and on the estimates of sediment volume. The article further presented a method for extrapolating data into an area lacking seismic coverage, corresponding to the territorial waters of the Vietnamese sector of the Beibu Gulf. The extrapolation relied on existing shoreline-change reconstructions, which enabled assumptions to be made regarding the characteristics of basin infill. Additional analyses of Beibu Gulf morphological changes were also carried out. Flow modeling, which allows to gain insight into transport directions and spatial sediment accumulation characteristics, provided further evidence supporting the hypothesis that Hainan Island serving as the source of the sediments. Visualization of changes in the seabed slope enabled the evolution of the basin to be described, revealing an aggradational stacking pattern corresponding to rapid sediment supply combined with sea-level rise between 65 and 56 kyr BP.

The third article, which concerned the Baltic Sea, focused on a comprehensive synthesis of data from various sources, resulting in a regional thickness model of Holocene sediments for the basin, as well as a set of paleogeographic maps with a time resolution of 500 years covering the past 11.7 thousand years. To generate the Holocene thickness model, several subsets of data were compiled from publicly available sources such as databases and scientific publications. Individual data subsets consisted of isolines, profiles, or points, and required interpolation using the kriging method. For areas lacking any data, extrapolation was performed using co-kriging and the U-net machine-learning algorithm. Generation of the first regional Holocene sediment-thickness model for the Baltic Sea enabled the estimation of sediment mass and annual sediment supply. A fully numerical paleogeographic reconstruction of the Baltic Sea for the Holocene was achieved by applying a conceptual model of relative sea-level change. It involved correction of the modern digital elevation model by glacio-isostatic deformation of the Earth’s crust (GIA), eustatic sea-level change (including independent water levels during the separation of the paleo–North Sea from the Ancylus Lake), and sediment dynamics. A set of paleo–digital elevation models (paleo-DEMs) was produced with a spatial resolution of 0.01° × 0.01° and a time resolution of 500 years. The paleogeographic maps were validated by comparison with existing reconstructions based on field observations. The article represents another step toward developing a coherent methodology for reconstructing the evolution of marginal seas during

transgressive–regressive cycles, encompassing not only tropical and subtropical climate zones but also polar and subpolar seas influenced by regional ice-sheet dynamics.

The submitted articles address the synthesis of various types of geological data that enable geostatistical modelling of the geometry of sedimentary series and their variability through time. The comprehensive interpretation of seismic and sedimentological data led to morphogenetic interpretations and allowed for additional spatial analyses to be carried out. The generated three-dimensional sediment thickness models, together with eustatic data and reconstructions of lithospheric deformation, constituted an essential component enabling fully numerical paleogeographic modelling. The articles also discuss the optimal methodology for generating three-dimensional models of sedimentary series, taking into account the specific characteristics of the input data; the synthesis of geological information from diverse sources; and a coherent methodology for paleogeographic reconstruction, based on a universal conceptual equation that incorporates regional conditions. Potential future challenges are also addressed, including erosion estimation, diversification of sediment accumulation rates, and broader consideration of shoreline morphogenetic processes.