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Lake-level changes and their controlling factors in some sub-basins of the Late Miocene Lake Pannon

THESES OF THE DOCTORAL (PHD) DISSERTATION

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Introduction

Sediments of the Late Miocene Lake Pannon and of the neighbouring deltaic and alluvial plains reach a thickness of a few kilometers in large parts of Pannonian Basin. Due to the hydrocarbon, lignite and thermal water resources which they contain, the economic importance of these deposits is also high. However, many questions about the evolution of the lake are still debated. Little is known about the variations of lake-level and its controlling factors (e.g. POGÁCSÁS et al. 1992, CSATÓ 1993, JUHÁSZ E. et al. 1996, VAKARCS 1997, SACCHI 2001, MAGYAR & SZTANÓ 2008), and it is questionable when and to which extent did the present-day mountainous areas form islands in the lake (e.g.. JÁMBOR 1980; cf. CSÁSZÁR ed. 1997). Positions of the sediment sources feeding into the lake are only known with high uncertainty, although information about them would help to answer many open questions about the palaeotopography of the lake floor, and — indirectly — about the structural evolution of the studied area.

From time to time, results suggesting direct connection between the Late Miocene water body of Pannonian Basin and the sea are published (e.g. NEVESSKAJA et al. 1987, BAKRAČ 2007). Nevertheless, neither the authors arguing for a lacustrine water body made it clear whether the lake was endorheic or it had fluvial outflow. A lot of information for solving these problems could be provided by the analysis of water-level changes, as the latter would have been probably tied to the eustatic sea-level curve in case of a direct marine connection, while an indirect effect of sea-level variations would have appeared in the presence of outflowing river(s). Modelling the water and salt budget of Lake Pannon could be also an effective tool in deciding the question of marine connection (cf. MAGYAR 2009).

Data about the Late Miocene climate of the Carpatho-Pannonian realm are scarce and sometimes controversial. The climate reconstructions are mainly based on paleontological research, therefore the study of the lacustrine sediments — which are generally good proxies for paleoclimate — could also provide new opportunities in this field.

Research on the ancient water-level fluctuations and sediment sources has major importance from the point of view of applied geology as well. Deepwater sand accumulations commonly form reservoirs of hydrocarbon or water, and their formation is generally related to water-level drops (POSAMENTIER & VAIL 1988, JOHANNESSEN & STEEL 2005). This fact can contribute to the prediction of reservoir bodies, however, the case studies supporting this statement were carried out in marine successions. The sediments of Lake Pannon provide an outstanding possibility for testing the connection between deepwater accumulations of coarse sediment and water-level changes in a lacustrine environment.

Aims of the study

This dissertation covers the study of the thick Late Miocene deposits of three sub-basins (Danube Basin, Zala Basin and Dráva Basin) of the Pannonian Basin. The sedimentary successions were analysed using mainly seismic stratigraphic data and well-logs. The primary aim of my work was to add new details to the paleogeography of the western part of Lake Pannon, especially regarding the features and locations of the sources supplying sediment to the deep basin. The paleomorphology of the lake floor and its temporal variation were mapped using 2D seismic profiles. Based on the results, it was attempted to answer whether the Transdanubian Range formed an island in Lake Pannon, and to estimate the timing of the onset of fold generation in Zala Basin.

Connecting the subsequent positions of the shelf-break on the seismic profiles across the study area, the water-level changes exceeding the vertical resolution of seismic profiles (30–40 m) can be identified (e.g. JOHANNESSEN & STEEL 2005, HENRIKSEN et al. 2009, HELLAND-HANSEN & HAMPSON 2009). The next objective of the study was to analyse these water-level changes for 9.8–6 Ma interval, during which the prograding shelf-slope passed over the studied area (cf. MAGYAR 2009). Tracing seismic reflections from the shelf to the deepwater areas made it possible to correlate lake-level changes with the coevally deposited deepwater sediments. Based on this correlation, the connection between lake-level variations and the formation of deepwater sand accumulations was examined. Such studies were only published about marine paleoenvironments as yet, although the results could be applied in hydrocarbon and water exploration in several sedimentary basins of the world.

A further aim of the dissertation was to reveal the factors controlling the reconstructed lake-level variations. For this purpose, it was necessary to establish a water budget model for Lake Pannon, on the grounds of literature data available on the extent of the lake, the salinity of inflowing and lacustrine water, and the paleomorphology of the possible catchment areas. From the results of calculations with the water budget model, new paleogeographical implications could have been derived. Amongst them, emphasis was placed on the questions of the hypothetical (direct or indirect) marine connections of the lake, as well as on the Late Miocene paleoclimate.

Methods

The study was based on the interpretation of a network of 2D seismic profiles with total length of about 3500 km, provided by MOL Plc in digitally processed, migrated version. This network covers an overall area of 12000 km^2 in Danube Basin, Zala Basin and Dráva Basin. The seismic profiles were visualized and interpreted using Landmark's GeoGraphix software. The

features of this software include the removal of the effect of post-sedimentary deformation from the seismic image, which was achieved by the method of SZTANÓ et al. (2007), i.e. flattening the profiles on a paleo-lake level estimated from the morphology of the shelf–slope–basin system.

MOL Plc. also made available the time-depth functions for 23 hydrocarbon exploration wells located close to the sesmic profiles. These functions made it possible to fit the well data on the seismic images which show two-way travel time as vertical dimension, and they allowed editing depth maps of the horizons interpreted on the seismic network. For the paleogeographical reconstructions, it was also necessary to calculate the decompacted thickness of sedimentary units. Decompaction was carried out by using the porosity data from the Pannonian Basin published by SZALAY (1982).

The assignment of sand ratio for given levels of the studied boreholes was based on the logs of resistivity, spontaneous potential and gamma-ray. These logs were available in digital format for 17 wells, and in printed version for 8 wells. All wells had several cored intervals, from which the documented lithologies were used for verifying the interpreted successions.

The depth and thickness maps of sedimentary horizons and units have been edited in Golden Software Surfer 8. The Monte Carlo simulations related to the water budget of Lake Pannon were carried out in Microsoft Excel 2003 and 2007, which were also used for editing the charts illustrating the results.

New scientific achievements (theses)

1. Sediments of the prograding shelf-slope of Late Miocene Lake Pannon proved to be divided into lobes, each of them covering a surface of 200–1000 km^2 in Danube, Zala and Dráva Basins. The lobes are bounded by reflection termination surfaces, indicating the temporary cessation of sedimentation and changes in the direction of progradation. Based on previous case studies (POREBSKI & STEEL 2003, FLINT & HODGSON 2005, LOBO et al. 2005), the material of the lobes was provided by point-like sources, probably the shelf-edge deltas of one ore more major rivers.

2. My results suggest that the studied part of the Danube Basin was infilled mainly by a single sediment source, reaching the area from the northwest. The variability of the dip direction of the ancient shelf-slope and the recurrently appearing southern and southwestern directions of progradation generally reflect the effect of basement highs (namely the Mihályi Ridge and the Transdanubian Range) forming barriers in the way of slope progradation. However, smaller watercourses heading eastwards from the Alps also contributed to the infill of the Danube Basin, building an individual lobe along its western margin. Another lobe, on the eastern part of the

Danube Basin, was formed by a river coming from northeast, the direction of Northwest Carpathians.

3. The interpretation of my thickness maps about the shelf-slope lobes made it apparent that the infill of Zala and Dráva Basins can be also explained by a single river flowing southwards, than finally southeastwards across these sub-basins. This river can be regarded as the ancestor of Danube, and its Late Miocene course could have been very similar to the Paleo-Danube known from the Pliocene (SZÁDECZKY-KARDOSS 1938, 1941, SÜMEGHY 1955, SOMOGYI 1961). However, avulsions could result in shifting of the river course by a few tens of kilometers to the east or west. In Zala Basin, this phenomenon is implied by the fact that the thickest parts of some shelf-slope lobes are not located south, but east or west of the previous lobe.

4. My results supported that the Transdanubian Range was elevated several hundred meters above the neighboring lake floor 9.7–9.0 Ma. The bulk of the elevated area was covered by shallow (not deeper than 150 m) water of Lake Pannon, which did not provide enough accomodation space for the formation of a prograding slope. In the same interval, the crest of Mihályi Ridge in the middle part of the Danube Basin was also a relative high covered by similarly shallow water.

5. Although Late Miocene deposits in Zala Basin are currently strongly deformed by folds, these structures had no major effect on the process of shelf-slope progradation. At Budafa anticline, such effect can be observed not at all, while Belezna anticline was found to be a slightly elevated zone of the lake floor in the time when the prograding shelf-margin reached it. These findings indicate that the formation of the anticlines, which is one of the earliest signs of the inversion of Pannonian Basin (FODOR et al. 1999, BADA et al. 2007), began about 8 Ma. As a result of mapping the thickness of shelfal deposits between selected seismic horizons, it turned out that sedimentation rate (proportional to subsidence rate) was already much lower above the present-day anticlines between 8 and 7 Ma. However, uplift and erosion still did not take place at that time.

6. My results show that Dráva Basin was reached by the shelf-slope from the north. However, the direction of progradation gradually turned from southern to southeastern, making it parallel to the axis of the recent basin, and implying that subsidence rate was already the highest along the current basin axis about 7 Ma. However, the thickness distribution of deepwater deposits do not suggest any significant difference between the subsidence rates of the marginal and central parts of the recent basin between 7.5–8 Ma.

7. Following the trajectory of the shelf margin of Lake Pannon, I recognized that the relative lake-level was moderately, continously rising between 9.8–8.9 Ma. That was followed by the alternation of intervals with quasi-steady and rapidly rising lake level between 8.9–6 Ma. This behaviour of water level can be considered as a unique feature of Lake Pannon, as similar phenomena have not been described before from any sedimentary basin. Twelve cycles consisting

of one interval of quasi-steady water-level followed by a rapid water-level rise have been identified, suggesting an average length of about 250 ky for the cycles.

8. Because the shelf-margin do not step below its previous position anywhere on the studied seisimic profiles, it can be stated that no significant drop of relative water-level took place in Lake Pannon between 9.8–6 Ma. As a consequence, it is not possible to set any third-order sequence boundary [*sensu* VAN WAGONER et al. (1988)] in the studied succession.

9. Correlating the sections of shelf-margin trajectory with the coevally deposited deepwater strata allowed me to detect that the sand ratio of the deepwater deposits did not decrease in the intervals of rising relative lake-level; moreover, generally a slight increase of sand ratio can be observed at the transition from steady to rising lake-level. This observation led to the conclusion that the rises of water-level were accompanied by major increases of sediment influx, as the latter can compensate the sediment trapping effect of the accomodation space created above the shelf. From a general point of view, I concluded that — in contrast to the situation in marine basins analysed in numerous studies (e.g. BURGESS & HOVIUS 1998, PIPER & NORMARK 2001, BULLIMORE et al. 2005, JOHANNESSEN & STEEL 2005, CARVAJAL & STEEL 2006, MUTO & STEEL 2006, POREBSKI & STEEL 2006, UROZA & STEEL 2008) — the largest deepwater sand accumulations are not necessarily related to intervals of lower relative water-level in the successions of hydrologically closed lakes.

10. I achieved the model of the salt and water budget of Lake Pannon. Through calculations based on this model, I proved that the known salinity of the lake (8–15‰) could have remain steady without any direct marine connection. The salinity could have been stablized by an outflow of a few 10 m^3/s, which probably occured through subsurface water. On the basis of the salt and water budget, it can be pointed out that Lake Pannon probably never had a surface outflow during the Late Miocene.

11. I reviewed the literature data available on the variations of the extent of Lake Pannon and the paleomorphology and paleoclimate of its discharge area. I proved that a reconstruction of the Late Miocene paleoprecipitation values of Central Europe can be carried out on the basis of the above data. Using this method, the annual precipitation was estimated to be 400–600 mm at the beginning of Late Miocene, increasing to 700–900 mm until 9.8 Ma. After that, the paleoprecipitation curve shows a gradual aridification, which seems to be accompanied by fluctuations of increasing amplitude, leading to variations between 300–500 and 500–700 mm for the end of Late Miocene. These fluctuations could play role in the development of both fourth-level cycles known from the shelfal successions and the longer-scale alternation of steady and rising water level introduced in this dissertation.

12. I disproved the hypothesis that the water-level of Lake Pannon could have been influenced by the tectonic deformation of the basement in a detectable degree. The results of my calculations

show that any change of the morphology of the lake floor would have been followed by the restoration of the equilibrium surface of the lake (a function of climatic and geographical conditions of the catchment area) in several thousand years. However, the deformations affecting the basement can become significant only on a much longer time scale.

13. My calculations indicated that the water-level of Lake Pannon was very sensitive on moderate changes in precipitation conditions. If decadal to centennial variability of the annual precipitation reached a level similar to the present one in Late Miocene, the lake-level could fluctuate by as much as 10 m within 30–40 years. I also introduced this phenomenon as a possible explanation for the rapid lake-level rises necessary for the preservation of the Bükkábrány fossil forest (KÁZMÉR 2008) and some other fossils from Lake Pannon.

Conclusions

Based on my research, it has been revealed that the shelf-slope of Lake Pannon is divided into lobes in Danube, Zala and Dráva Basins. The formation of these lobes suggest that the shelf-edge was reached by deltas of major rivers. Although the observed directions of slope progradation are not uniform, their spatial distribution can be explained by the autocyclic variability in the deltaic system of a single river reaching the studied area from the north–northwest and by the effect of basement highs forming barriers in the way of slope progradation. The Transdanubian Range and Mihályi High were found to be such barriers covered by water significantly shallower than the neighbouring areas. The anticlines of Zala Basin only slightly affected the progradation of the slope, however, there influence on the thickness of the shelfal succession is already considerable. These findings indicate that the folding of this area (one of the earliest signs of the inversion of Pannonian Basin, cf. FODOR et al. 1999 and BADA et al. 2007) began about 8 Ma.

Connecting the subsequent positions of shelf-break along seismic profiles it has been recognized that the relative water level of Lake Pannon was moderately rising between 9.8–8.9 Ma, than intervals of quasi-steady and rapidly rising relative lake level alternated with an average period of 250 ky between 8.9–6 Ma. Surprisingly, the sand ratio of the deepwater deposits did not decrease during lake-level rises, moreover, the units deposited in these intervals usually contain slightly larger proportion of sand. These features can be explained if the lake level was risen by increasing humidity of the climate: more precipitation results in enhanced erosion on the discharge area, providing enough sediment to keep up with the increase in accomodation space.

The above scenario can be realized only in an endorheic lake, therefore it was necessary to examine whether Lake Pannon could be hydrologically closed. For this purpose, the model of the salt and water budget of the water body has been achieved. Calculations based on this model proved

that subsurface outflow of a few 10 m^3/s could keep the brackish salinity stable in the lake. Without any surface outflow, the extent of the lake is controlled only by the climate of the discharge area, making it possible to use lake surface as a paleoprecipitation proxy. The results show that annual precipitation was 400–600 mm at the beginning of Late Miocene, gradually increasing to 700–900 mm until 9.8 Ma, than falling to about 500 mm for the end of Late Miocene, accompanied by fluctuations of increasing amplitude.

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