EÖTVÖS LORÁND UNIVERSITY – FACULTY OF SCIENCES

DEPARTMENT OF GEOPHYSICS AND SPACE SCIENCES

ENVIRONMENTAL GEOPHYSICAL STUDY OF WATER SEISMIC PROFILES AT LAKE BALATON

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Master in Environmental Sciences

Theses of the PhD dissertation

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Introduction

The area of Lake Balaton has been studied by seismic surveys since 1993 under the guidance of the Department of Geophysics and Space Sciences, Eötvös Loránd University, Budapest. During the last 25 years, about 2000 km of high to ultrahigh resolution seismic profiles were measured in the framework projects supported by the Hungarian National Research Found and international cooperations. These surveys have provided a unique database to investigate sedimentary strata and tectonic features below the lake (Tóth et al. 2010). Former seismic studies have already led to various results in the area that can be only fully understood by integrated interpretation of geological, geophysical and environmental data, which was accomplished during this PhD work.

The strata below Lake Balaton are composed of three megastratigraphic units. Above the acoustic basement in a depth of 10 to 250 m Late Miocene deltaic sediments can be found that are related to one of the basin margin depositional systems of Lake Pannon (Pannonian strata). On the top of the Pannonian strata various sediments of the Quaternary have been mapped, which were originally related to two different environments. The lower part is composed of Pleistocene fluvial-alluvial strata bounded by erosinal unconformity both at the bottom and top. The younger succession is composed of latest Pleistocene-Holocene mud deposited in Lake Balaton. The latter is horizontally stratified and often saturated by shallow gas.

Early investigations at Lake Balaton focused on studies of the Siófok sub-basin, where the low gas content of the lacustrine mud provided favourable conditions for seismo-acoustic surveys. These surveys mapped Pannonian strata and tectonic features below the lake (e.g., Sacchi et al. 1998; 1999; Bada et al. 2010; Horváth et al. 2010), the Pleistocene fluvial strata and morphology of the bottom of the lake (e.g., Novák et al. 2010; Zlinszky et al. 2010).

One of the main goals of my PhD study was to integrate the seismo-acoustic data of the last 25 years into a single database and carry out a comprehensive interpretation using both geophysical and environmental approaches. My work included both stratigraphic and tectonic interpretations of the Pannonian and Quaternary strata.

Investigation on the Pannonian strata was focused on stratigraphic division and the reconstruction of the Late Miocene paleo-enviroments, and included the following main questions:

- What kind of stratigraphic units build up the Pannonian strata, and what is their internal architecture?

- How did the depositional systems look like in the Late Miocene and what kind of rocks can be related to these sedimentary environments?
- What was the main direction of the sediment transport and what kind of conditions could influence sedimentation in the area?
- Were there any significant relative lake level changes during the Late Miocene?
- How did the Late Miocene paleo-environment look like at the southern foothills of the Transdanubian Central Range?

During the *tectonic investigations* I concentrated on the fault system below Lake Balaton that was previously interpreted in the Siófok sub-basin as a shear zone (Bada et al. 2010). I have made a structural mapping of the whole area, I attempted to answer the following basic questions:

- What kind of individual faults can be mapped in the shear zone and how they fit into a kinematic pattern?
- What is the nature and extent of the vertical and horizontal displacements along these faults?

In the course of *research related to the Quaternary strata* I focused on mapping of the fluvial and lacustrine sediments. My main aim was to understand Pleistocene to Holocene environmental changes that resulted in the transition of the early fluvial system into a set of separate lacustrine sub-basins and eventually to a unified large lake that were previously suggested in the literature.

Finally, I have examined the *shallow gas system in the mud of Lake Balaton*, which shows up as various gas anomalies in the seismo-acoustic profiles. I attempted to address the following problems:

- What kind of seismic anomalies can be seen in the seismo-acoustic images and what kind of conditions can generate them?
- What is the spatial distribution of the gas anomalies? Is there any regularity in the distribution pattern?
- Can we observe any seasonal changes in the existence and extent of the gas anomalies and if so, what is the reason of these changes?
- What is the origin of the gases in lake sediments and to what extent are they compatible with the Quaternary evolution and structural deformation of the area?

I have tried to summarize all my observations and interpretations in this work to make my dissertation a good starting point for future studies that will deal with the environmental or geological conditions of Lake Balaton or the surrounding area.

Applied scientific methods

During my research I carried out seismic mapping and interpretation by the use of the Kingdom 8.5 geophysical software. Seismic investigations were based on classical geological methods and geophysical data. I have compared the observed seismic geometries with borehole data, geophysical logs, geological and geophysical maps, digital elevation models and descriptions of nearby outcrops to understand those environmental processes that created the strata below the lake.

The new aspect in this research was the quality and extent of the data that used for research. My main tasks was to create a unified databank from the previously recorded seismic profiles of various resolutions and penetration depths. Integrated interpretation of seismic data have been done in different scales by comparing different kind of seismic images. During my PhD work I also participated in the improvement of the seismic database by planning and coordinating of new surveys and the data processing campaigns. New surveys were focused on the rather unknown western parts of the lake to reach a good seismic coverage for the whole area. I have also participated in data recovery and processing of high-resolution profiles from the first surveys in 1993. As a result of this work, records on VHS videotapes have been converted to a digital format and fit into the new database. With including these profiles to the database comparison of previously published works became possible.

Results and Theses

In my PhD dissertation I describe my observations, interpretations and conclusions in four main chapters. I addressed the first chapter to the investigation of the Pannonian strata, while the second, third and fourth chapters contains my new observations, ideas and their discussion in connection with the structural deformation, Quaternary sediments and shallow gas system below the lake. My main results and the most important findings are summarized in the following theses:

(1) The Pannonian strata below Lake Balaton have a thickness of more than 200 m. This strata can be divided into fourth to fifth order parasequences in accordance with former

study of Sztanó & Magyar (2007). These parasequence boundaries are related to minor transgressional events and can be regionally mapped with the help of the ultrahigh resolutions data. Larger stratigraphic units can be also distinguished and interpreted as deltaic cycles or delta complexes according to Sztanó et al. (2013). In the high-resolution dataset 3 major delta cycles can be mapped. These cycles suggest that delta construction in the area took place above an eastward rising basement and the progradation of deltas mainly pointed towards the East. I explained this unexpected progradation pattern with the presence of a major deltaic system, which crossed the Transdanubian Central Range through a narrow gateway of the Tapolca-Sümeg trough and expanded laterally before sedimentation could continue towards the major depocenters to the South.

(2) Comparing borehole data and seismic images I conclude that the parts of the Late Miocene deltaic system can be correlated with basin margin lithostratigraphic units (Szák Formation, Somlói Member, Tihanyi Member). Results show that the Somló Member in the area of Lake Balaton corresponds to the foreset of those early Pannonian deltas that first filled up the area and created a uniform deltaic plain. Prodelta sediments of the previous deltas showed a good correlation with the layers of the Szák Formation, while their topset deposits and the younger and thinner delta cycles could be assigned to the Tihany Member.

(3) With mapping the fault system in Pannonian strata below Lake Balaton I found that the vertical displacement along the faults are strongly limited, in the order of 0.1 to 15 m. I interpreted the fine structures below the lake as elements of a wide shear zone that can be mapped in both the Szemes and Siófok basins. Comparing the observed fault pattern with classical structural models and analogue model experiments I inferred that the shear zone below the lake is left lateral in sense. Fault pattern showed duplex structures, among which the most spectacular one was identified below the Szemes basin.

(4) Comparison of the fault pattern at Lake Balaton with analogue model experiments I conclude that the horizontal displacements along the fault zone are also limited. Multichannel profiles across the Szemes basin and structural interpretation of the Balaton Line offshore to the south of the lake have suggested that the maximum horizontal displacement along the shear zone is on the order of few 100 of meters.

(5) In Quaternary strata I could point out two different environmental stages. The younger stage is related to Lake Balaton, while the older stage is associated with alluvial-fluvial sediments preceding the recent lake. My observations show the existence of a pre-Balatonian river system, which left behind oxbow lakes at the end of the Pleistocene.

In these oxbow lakes peat could accumulated just before the onset of the lacustrine conditions.

(6) I showed that a Pleistocene lake terrace was situated at the southern part of the western lake basins. Based on reflection correlations I conclude that this rim was only flooded during the Holocene, after the formation of the unified lake. According to seismic data the flooding of this rim was not only controlled by lake level rise but the elevation of the Transdanubian Central Range could also affect this event as it induced southerly tilt of the lake basin.

(7) During the study of the lake mud I made a detailed review on the shallow gas system of Lake Balaton. I grouped the observed gas anomalies into 8 basic types and 3 different gas levels regarding their acoustic characteristics and stratigraphic position. By mapping the different anomaly types and gas levels I demonstrated some spatial and temporal changes in the gas system. I found that the presence of free gas in mud is quite stable below the half of the lake, however the depth of the gas saturated zone is temporary variable. About the two-thirds of the other half of the area is characterized only by minor gas accumulations, while the rest of the place (about 1/6 of the lake area) shows large spatial and temporal variations regarding gas saturation. My observations suggest that gas fronts in the lake mud are much shallower and more extensive during the end the each summer and during the fall relative to the spring or the beginning of the summer.

(8) Investigating the gas anomalies situated in the lower mud I showed that gas saturation at this place is stable in time and associated with Pleistocene peat accumulations and gas migrating up from deeper strata. In contrary, shallower gas fronts were find to be temporary variable. Stable gas fronts in the near-shore area showed gradual transition towards the open water that manifests in breaking up and deepening of the upper mud gas level. I explained these changes with uneven distribution of the organic matter in mud, changes in solubility and microbial activity. I conclude that changes in the gas system is primarily manifest in disappearance and building up of different gas levels. Smaller seasonal shifts in the depth of each gas fronts are only secondary. I have illustrated all these changes of the gas system by simplified qualitative models.

(9) I analysed the possible sources of the shallow gas on the basis of my seismic observations and scientific literature. I conclude that the principal source of the free gas is methane produced from organic matter of the lake mud. In addition, I suggest that transport of CO_2 by groundwater flow to the lake mud along faults is also an important factor. I summarized my model in a hypothetic cross-section across the lake.

Main conclusions and future plans

As a result of my PhD work I conclude that seismic profiling in the area of Lake Balaton is an extremely powerful tool to make high to ultrahigh resolution geological and environmental investigations in the southern foreground of the Transdanubian Central Range. Combining different methods with various resolutions and penetration depths we can understand the paleo-environments below the lake both on local and regional scale and in a relatively long timeframe. Although this method proved to be really useful in structural and stratigraphic studies, it cannot explain every aspect of the environmental conditions, especially those that are related to the shallow gas system of the lake. To understand all aspects and changes in environment one should combine geophysical data with the results of other disciplines (e.g., limnology, hydrobiology, microbiology, sedimentology and geochemistry) in the framework of a broad scientific cooperations. In my thesis I tried to point out all those questions and observations that could be useful for such a work and could provide a good basic for the future studies that may bring us a step forward to the understanding of our treasure, Lake Balaton.

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