# GEOPHYSICAL SURVEYS OF A YOUNG STRIKE-SLIP FAULT ZONE AT LAKE BALATON AND THEIR GEODYNAMIC INTERPRETATION

(A BALATONI VONAL: EGY FIATAL OLDALELMOZDULÁSOS VETŐZÓNA GEOFIZIKAI)
KUTATÁSA ÉS AZ EREDMÉNYEK GEODINAMIKAI ÉRTELMEZÉSE

## Final Report

**NKFI Project K 109255**

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# The principal aim of the project

The working hypothesis of the project was the assumption that the fault system observed below the Lake Balaton by seismic surveys and other geophysical measurements (*Figure 1.*) is tectonically similar to NE-SW striking regional shear zones of the Pannonian Basin (e.g. Balaton Line, Mid-Hungarian Line etc.). The lake surface offers an ideal site for high resolution geophysical surveys, primarily single- and multichannel seismic data acquisitions (*Figure 2.*). Detailed and high quality data in the area shall lead to geodynamic interpretations, which are relevant to the neotectonics of the entire Hungary and Pannonian basin. Towards this end the following scientific investigations were realized and results achieved are summarized below:

1. ***Integrated interpretation of single and multichannel seismic sections measured on the lake since 1993***

*Figure 2* shows the available seismic sections on the lake which consists of two subsets of data: seismic lines that were available in 2012 (i.e. at the start of the project) and new lines acquired during the project (until the end of 2017). New lines were deliberately designed to address key problems like:

- termination of fault lines at the eastern margin of the lake,
- their passage to land (Balatonfő Region),
- western branch of the fault system in the vicinity of Balatonboglár area and
- precise location of the fault zone in the Tihany area, particularly in the Tihany Strait.

In order to facilitate integrated and complete interpretation of seismic data a large Kingdom database has been constructed to allow simultaneous use of all geophysical data to arrive at the best possible interpretation of faults and key stratigraphic horizons mapped by high to ultrahigh resolution seismic lines. Characteristics of different seismic surveys, e.g. penetration depth, frequency range and vertical resolution are listed in *Table 1.* The sections image a marked acoustic basement represented by the top of synrift strata (mostly late Upper Miocene limestones). This implies that all the mapped features are postrift tectonic elements.

According to all available data the shallow water (0-5 meter) of Lake Balaton is underlain by a 0-6 meter, horizontally stratified Holocene to Late Pleistocene calcareous mud, resting unconformably on Pleistocene fluvial deposits and/or Late Miocene (Pannonian) strata. Seismic survey campaigns imaged all of these sedimentary layers below the lake down to the acoustic basement (Sarmatian or Paleozooic rocks). The summary of these lithostratigrapic units is shown in *Figure 3.*

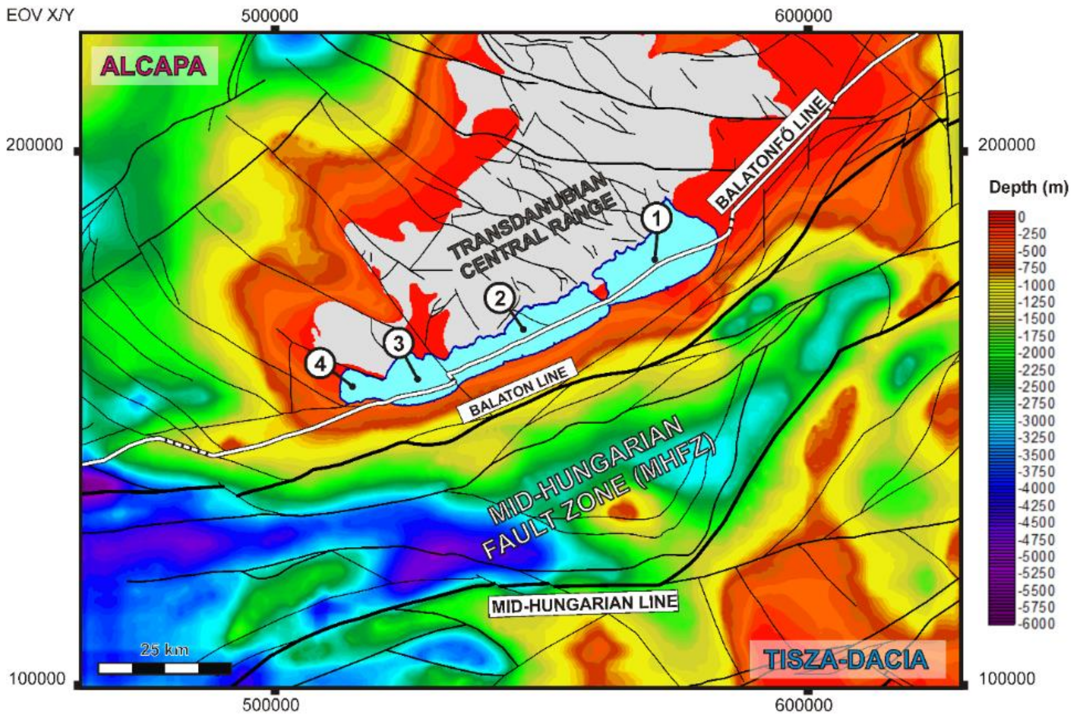


**Figure 1.** Tectonic structures and basement depth in the study area (after VISNOVITZ ET AL. 2015B). **(1)-(4)** are the sub-basins of Lake Balaton: Siófok, Szemes, Szigliget basins and Keszthely bay resp.


**Figure 2.** Maps showing high to ultrahigh resolution seismic profiles at Lake Balaton. Black lines indicate 2D lines that were available in 2012 at the begging of the projects, red lines indicate profiles that have been recorded during the project period, between 2013 and 2018.

| | Frequency Range | Penetration | Vertical Resolution | References |
|---|---|---|---|---|
| MCS | 0.1 – 1 kHz | 100 – 500 m | 3 – 10 m | TÓTH 2009, NÉMETH 2013 |
| HiRes | 0.5 – 5 kHz | 100 – 150 m | 0.5 – 1 m | SACCHI 2001, VISNOVITZ ET AL. 2013 |
| UHiRes | 1 – 10 kHz | 5 – 40 m | 0.1 – 0.3 m | TOTH ET AL. 2010, BALAZS ET AL. 2013 |

**Table 1.** Characteristics of the difference type of 2D offshore seismic surveys used for interpretation

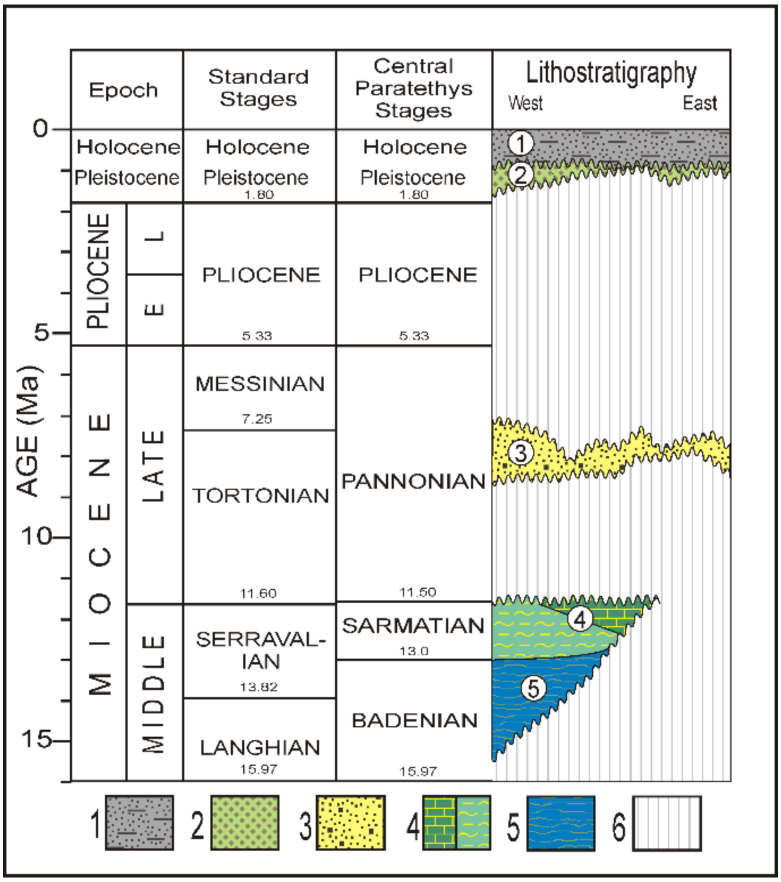


**Figure 3.** Lithostratigraphic units in the area of Lake Balaton (VISNOVITZ ET AL. 2015B)
1= Holocene calcareous mud; 2= Pleistocene fluvial strata; 3= Pannonian sedimentary rocks: Tihany, Somló and Szák Formations; 4= Sarmatian calcareous marl and biogenetic limestone: Kozárd and Tinnye Formations, resp.; 5= Badenian marine shales: Szilágy Formation; 6= Stratigraphic gap.

Tectonic interpretation of nearly 2000 km long high-resolution reflection profiles recorded by different acquisition techniques have led to the following main conclusions:

1) The characteristic tectonic features of the area are decimeter to meter scale faults and folds in the gently dipping (1-3°) Late Miocene (Pannonian) strata.
2) Imaged faults are parts of a few kilometers wide left lateral wrench fault zone that is quasi-parallel with the lake longitudinal axis (*Figure 4.*). This fault zone is the continuation of the Balatonfő line known onshore to the East of the lake (*Figure 1.*).
3) The formation of Lake Balaton has primarily been controlled by lake parallel wrench faults as opposed to the traditional concept (LÓCZY 1913, CHOLNOKY 1936) which considered the lake basin as normal fault-controlled rift graben.

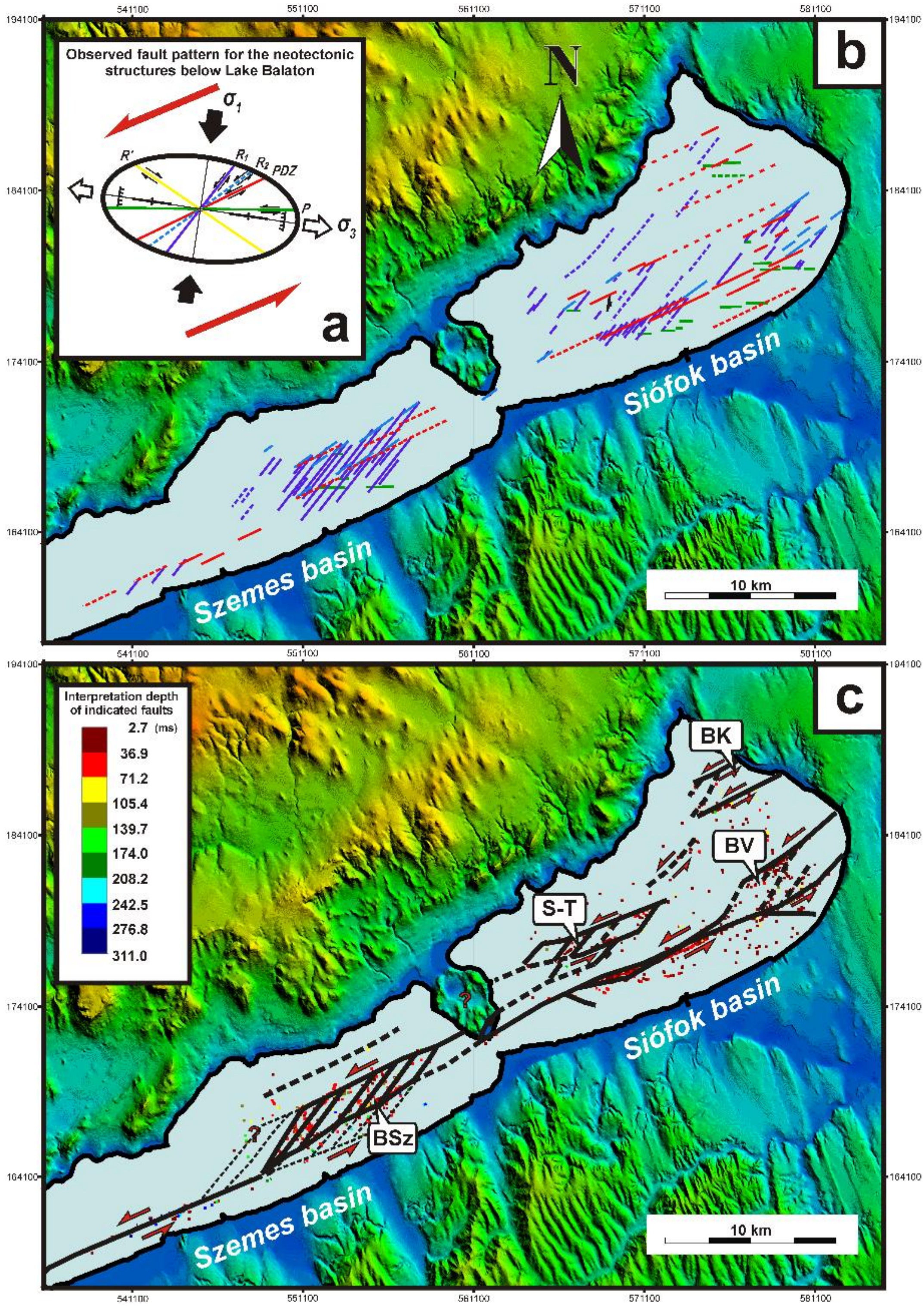


**Figure 4.** Structural model of the fault system below Lake Balaton (VISNOVITZ ET AL. 2015B). a: observed fault pattern, b: fault segments classified along the fault pattern, c: structural model. BSz, BK, BV, S-T are locations where fault segments are connecting to each other forming tectonic small scale duplexes.

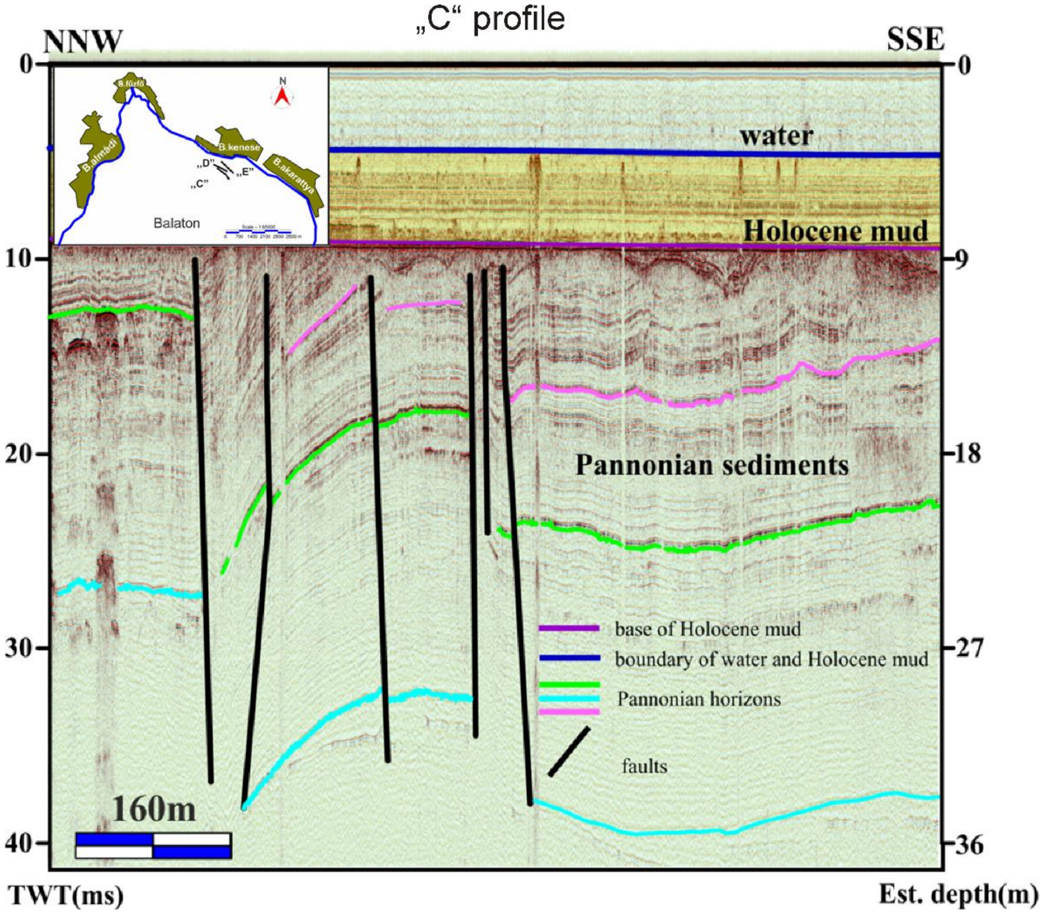


**Figure 5.** Example of an ultrahigh resolution strike-slip fault zone close to the offshore-onshore transition at Balatonkenese (based on JAKAB ET AL. 2017)

The location of the offshore-onshore transition has been a subject of data acquisition in 2014, 2016 and 2017. The new data confirmed the fault map in *Figure 4. a,b,c* and offered a spectacular example of the geometry of the left-lateral strike-slip fault at the very eastern margin of the lake (*Figure 5.*).

Seismic surveys in 2014 around Tihany peninsula also yield supporting information of fault pattern in *Figure 4. a,b,c* and led to detailed lake bottom morphology of this deepest part of the lake (Tihany Well). Migration of the Tihany Well can be inferred by comparison with previous bathymetric maps and this is most likely the consequence of lake currents (seiche) which accelerate in the narrow strait (KISS ET AL. 2018).

## 2. *Magnetic mapping of potential volcanic bodies below the lake and joint interpretation with the seismic data*

Basaltic volcanic activity at the Balaton-Highland region has been long known and recently reliably dated by $^{40}Ar/^{39}Ar$ technique (WIJBRANS ET AL. 2007). Most of the age data are in the range of 2 to 6 Ma, however the Hegyestű and Tihany volcano are out of this range with their 7.94 and 7.96 Ma plateau age values, respectively.

Magnetic anomaly map of Hungary, based exclusively on classical land surveys (KISS J. & GULYÁS Á. 2006) shows a typical pattern of paired positive and negative magnetic anomalies (dipole field) in association with these basaltic volcanoes. This is an indication that the main source is remanent magnetization acquired shortly the intrusion of magmatic mass during the thermal relaxation. These basaltic butes are located mostly in the Balaton Highland area, however they also occur at a few localities (Balatonmária, Fonyód, Balatonboglár) to the South of the Lake. Therefore, it is possible that basaltic intrusions occurred below the lake as well and subsequent tectonic activity might have influenced their geometry.

To address this problem a systematic magnetic survey has been devised and performed on the whole lake (VISNOVITZ ET AL. IN PREP.) along the grid shown in *Figure 6.* After applying the adequate temporal and spatial corrections of raw total field data, a vertical component (dZ) magnetic anomaly map was constructed and fit to the national magnetic anomaly map (dZ) of Hungary (*Figure 7.*). The most remarkable features of the new map are the continuation of the magnetic anomaly pattern related to Badacsony volcano, possibly Tihany, Balatonboglár and Balatonmária as well. Small and fairly well defined positive anomalies can be seen in the inner part of the eastern (Siófok) sub-basin and an elongate, narrow, low amplitude feature in the central (Szemes) sub-basin (*Figure 7. and 8.*). Interestingly, both anomaly patterns show good correlation with the shear zone mapped by seismics (*Figure 4.*), hence we speculate that these are related to the fault activity (*Figure 8. and 9.*). Clarification of this observation requires further measurements, possible drilling and quantitative modellings.

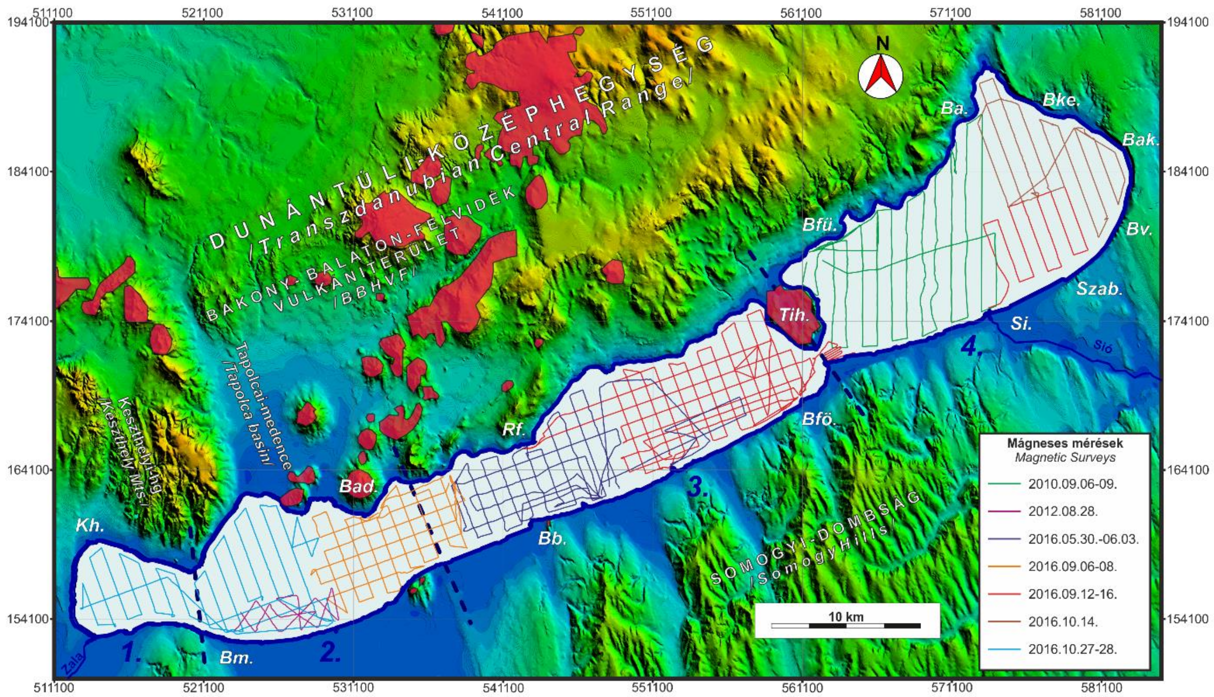


**Figure 6.** Magnetic survey lines in Lake Balaton and outcrops of basa rocks (based on NÉMETH 2012) in the area. Colours of survey lines indicate different acquisition periods.

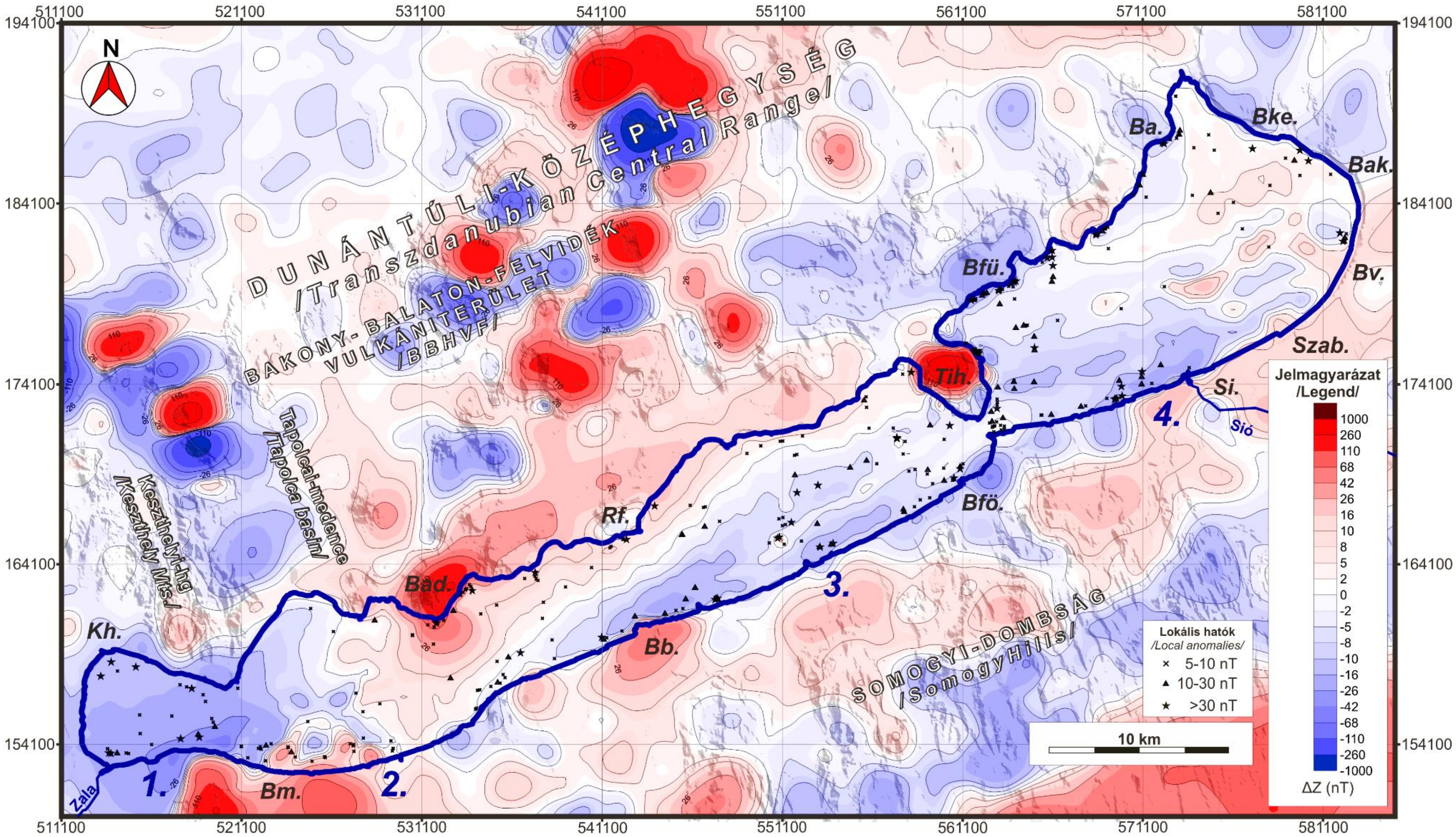


**Figure 7.** Magnetic (ΔZ) anomaly map of Lake Balaton and its surroundings (based on VISNOVITZ ET AL. 2017 and KISS & GULYÁS 2006)

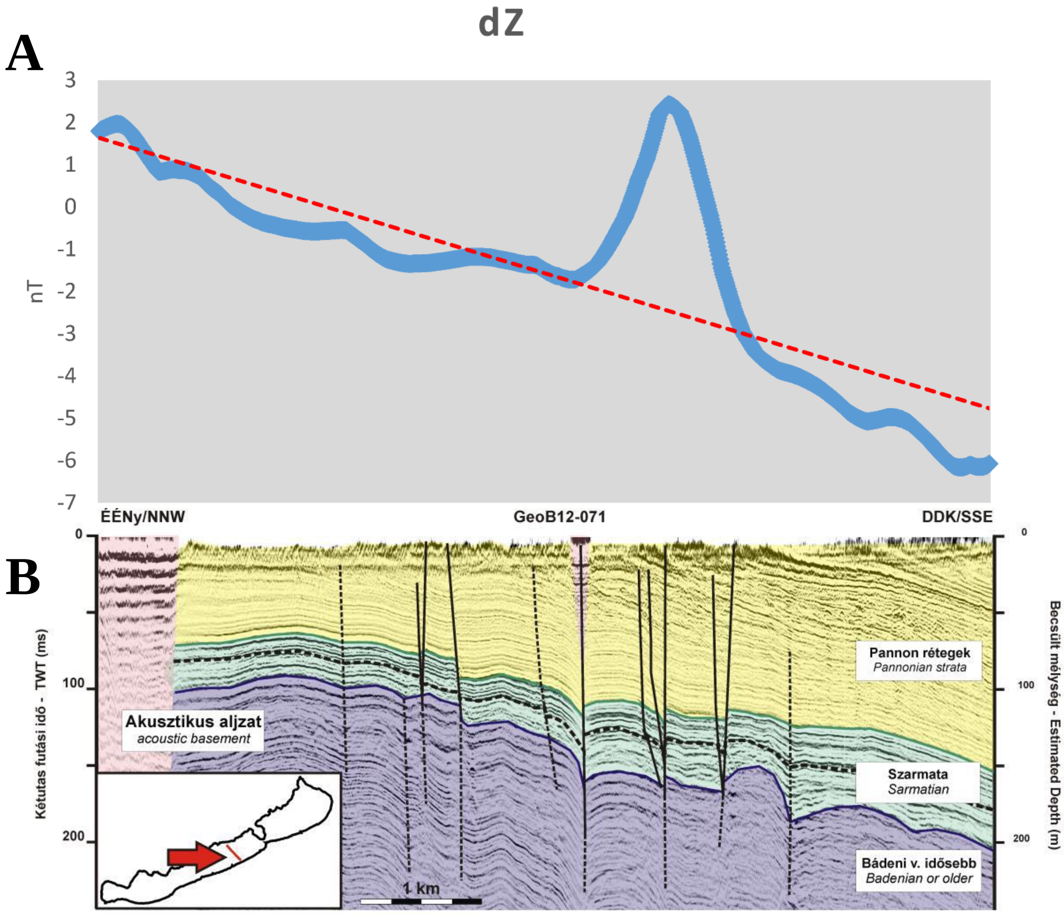


**Figure 8.** Correlation between the low amplitude elongate magnetic anomaly and faults in the central sub-basin of Lake Balaton (after HEGYI 2017)

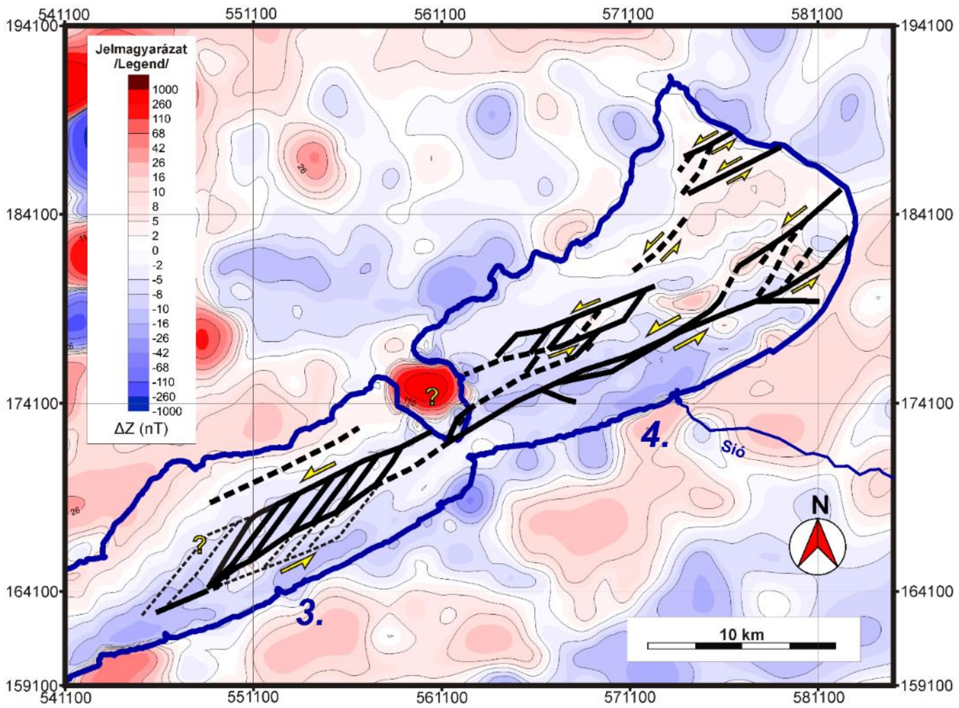


**Figure 9.** Comparison of magnetic (ΔZ) anomalies with interpreted fault segments (based on VISNOVITZ ET AL. 2015B and VISNOVITZ ET AL. 2017)

## 3. *Seismic slip rate inferred from Lake Balaton geophysical data*

Regarding to the small magnetic anomaly features we have regretfully concluded that there are no larger volcanic masses below the lake, which could have been offset remarkably by the mapped fault system. Therefore, there is no possibility to infer neotectonic slip rate from sheared volcanic masses as we initially hoped.

However, our dense seismic grid system led to a very high-resolution pattern of faults which can be used to estimate the tectonic to slip rate. It is because classical analogue laboratory (clay cake) experiments show the regular pattern of shear fault systems and their systematic evolution with increasing horizontal offset (e.g. TCHALENKO 1970). Comparison of the observed and clay cake fault pattern led to the following conclusions (VISNOVITZ ET AL. 2015B):

1) The shear zone below Lake Balaton has very similar fault pattern with those in classical analogue models (Riedel experiments of TCHALENKO 1970).
2) Comparison of model results with the observed fault pattern below the lake suggests small horizontal offset (few hundreds of meters) along the fault system. This can be verified by direct measure of normal offset of faults across Balatonszemes pull-apart duplex.
3) A neighbouring first order wrench zone (Balaton Line) imaged by a top quality 3D industrial seismic cube to the South of the lake (Buzsák 3D) exhibits similar left-lateral secondary fault pattern to those below Lake Balaton. We infer that the shear zone below the lake was controlled by the same stress field as the major neotectonic wrench faults in the Pannonian basin.
4) We infer that the strike-slip offset along the first order Balaton line is also small, in the range of 1.0-1.5 km. This means a 0.2 to 0.3 mm/year average slip rate during the neotectonic phase (8 to 0 Ma) of the area.

The most recent monitoring of crustal movements in Hungary took place in the framework of seismic and tectonic hazard assessment of the site of the Paks 2 nuclear power plant (MVM PAKS II. ZRT, 2016). GPS monitoring and satellite radar interferometry surveys of the large part of Hungary were carried out and the results clearly demonstrate extremely small rates of deformation, usually in the range of 0.1 – 0.2 mm/year, or even less and the lack of correlation with seismically mapped regional fault systems. This implies that Hungary is currently characterized by very small rates of crustal deformation and seismotectonic movements are below the present accuracy level of space geodesy.

## 4. *Additional studies, which were not included in the original working plan*

### *4.1. Studies of mud gas*

In the course of realization of the project it was recognized that “noise” in ultrahigh resolution seismic data have a physical reason which is related to local gas saturations in Lake Balaton’s mud and topmost Pannonian strata.

This initiated a systematic study and mapping of the seismic “noises” and we arrived at the following main results (VISNOVITZ ET AL. 2015A):

1) The “noises” caused by shallow gas occurrence in the sediments appear in various forms and three functionally different gas levels can be distinguished (upper, middle, lower).
2) The lowermost level at around the base of the mud is a fairly permanent, and is related to peat accumulations, fluid discharge and tectonic fault zones below the lake. In contrast, the upper and middle levels show high temporal variation in depth and extent, and controlled by biogenic methane production and solubility variation. The seasonal variability can be attributed to solubility variations caused by changing annual temperature, water level fluctuations, and the seasonal variability of CH4 production and consumption, therefore influenced by numerous environmental factors.
3) The understanding of the seasonal variability of gas saturation in mud has facilitated the proper panning of nearshore seismic data acquisition for time periods of the least gas saturation.

### *4.2. Reinterpretation of former Vertical Electrical Sounding (VES) profiles*

We have realized during our project activity that an unpublished set of geophysical data at the Lake Balaton exists comprising few hundreds of vertical electrical sounding curves along 15 profiles across the lake with a length of 5-10 km. These measurements were carried out by the Eötvös Loránd Geophysical Institute between 1970 and 1990 guided by Balázs Magyar who were available for consultancy. During the project we digitized the old scanned field protocols and a complete digital dataset was constructed.

Interpretation of the sounding curves basically distinguished the low to medium specific resistivity (20 to 50 Ωm) Miocene to Pannonian sediments from the usually higher resistivity (50 to few 1000 Ωm) Mesozoic and/or Palaeozoic basement. This offered a new and independent geophysical information on the basement morphology below the lake (e.g. *Figure 10.*). In general, we have found a good agreement between the structural features derived from shallow seismics and electric sounding data.

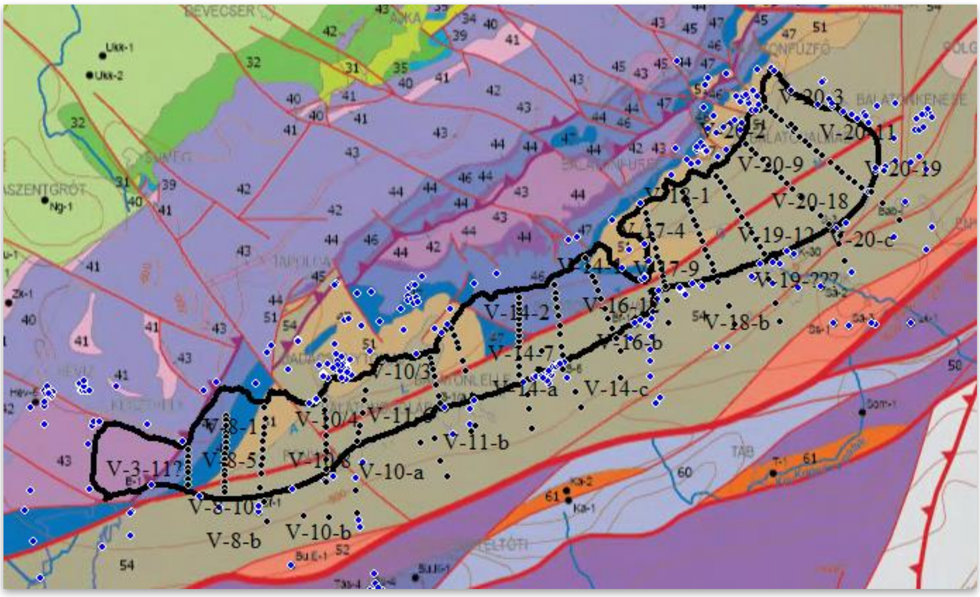


**Figure 9.** VES data organized into digital base during the project (MEDNYÁNSZKY 2017). Black dots indicate location of VES soundings, blue dots show position of nearby boreholes.

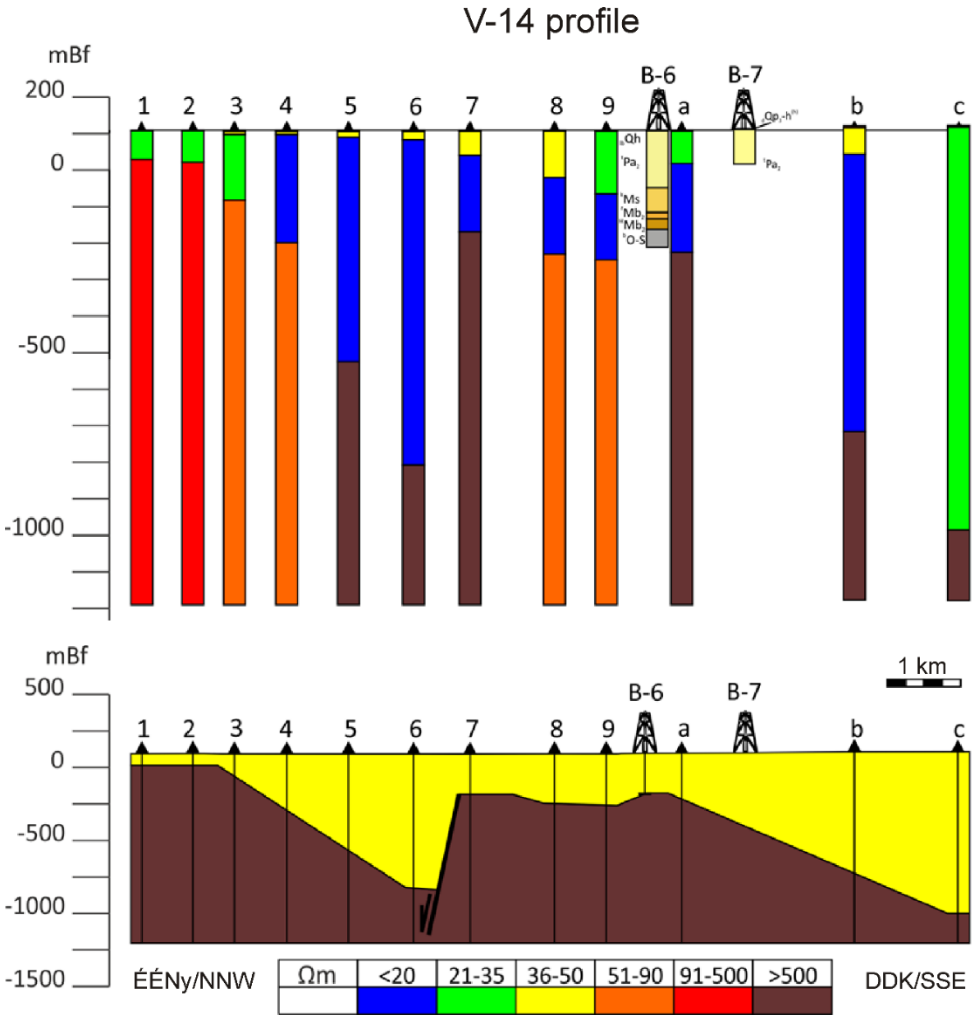


**Figure 10.** Example profile showing the results of VES data inversion. Upper image shows the results of inversion, lower image shows the simplified geology (MEDNYÁNSZKY 2017)

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