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Summary of the Ph.D dissertation

Cenozoic structural evolution of the southern Bükk foreland

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1. INTRODUCTION AND OBJECTIVES

My doctoral research is an integral part of a more comprehensive state-funded project whose aim is to investigate the Miocene-Pliocene deformational history and depositional environments of the Pannonian Basin. The southern Bükk foreland is a key area of this project because it is bordered by some main structural zones playing an important role not only in the escape of major tectonic units during Early Miocene but also in the evolution of the Pannonian Basin.

The objective of my research is to unfold the Cenozoic structural evolution history of the area, to map the major fault patterns and to better understand the temporal activity and kinematics of major structures. The integration and comparison of delineated deformational phases with those of the Pannonian Basin was another important aim of the research.

2. APPLIED METHODS

2.1 Field observations, measurements and their evaluation

Structural observations and measurements were implemented in the southern part of the Darnó Deformation Belt (DDB) and in the southern Bükk foreland. 78 sites/outcrops were investigated during which the orientation of major structural elements was in the focus of my interest. Fault planes with slickensides were used to calculate paleo-stress field by means of Angelier's algorithm (1984). Structural data without kinematic indicators were also used to estimate the position of stress axes by using Anderson's method (1951). The calculated and estimated paleo-stress fields were put into structural phases whose ages were determined on the basis of syn-sediment deformation, the result of tilt test, paleomagnetic data (Márton & Pécskay 1998), earlier structural observations (Márton & Fodor 1995; Csontos 1999; Fodor et al. 1999; Fodor 2010) and the new radiometric ages of different pyroclastic levels (Lukács et al. 2014,2015).

2.2 The investigation and collection of core samples

The cores of crucial wells (Szv3, Mn-2, and Tiv6) were sampled with the aim of determining the U/Pb radiometric and paleontological ages of key levels thus we could specify the stratigraphy of the area. Many samples were taken for the purpose of measuring vitrinite reflectance in order to use them in the subsidence modelling.

2.3 The interpretation of seismic profiles and making maps

Nearly 80 two-dimensional time-migrated seismic profiles in the Vatta-maklár Trough (VmT) and a three-dimensional seismic block (Polgár 3D) located south of the interflow of the Tisza and Sajó rivers were available. 8-10 horizons were picked and correlated by using hundreds of wells with re-evaluated stratigraphical data, geophysical log data, time-depth charts, magnetostratigraphic levels (Elston et al. 1994) and new radiometric age data of pyroclastic rocks (Lukács et al. 2014,2015).

The major structures were also interpreted and correlated to make fault polygon maps for different time levels. Two-way travel time and thickness maps were also made to investigate the temporal activity of tectonic structures. The analysis of along-strike variation of the throw values of major faults revealed the junction points of fault segments. To enhance fault zones and volcanic features different seismic attribute maps were implemented. Self-similar neural network made from the combination of different seismic attributes was used to identify groups with similar seismic properties. Sills and hydrothermal vents/mounds were delineated successfully by using this method.

The structural maps/models of different deformational phases were compared with previous models, ideas to investigate the similarities and differentiation and their possible reasons.

2.4 Balanced cross-sections

Two out of 80 two dimensional seismic profiles (HI-D, mk-23) in the VmT were chosen to make balanced cross sections (in Move 2013 software) which represent the best the temporal and kinematic activity of major faults in western and eastern part of the VmT. The measure of extension/compression with special emphasis on the base Pannonian level were also estimated along the section.

2.5 Subsidence history modelling

Three boreholes (Szv3,Mn2,Tiv6) representing the best of the study area were used to make 1D subsidence modelling by means of Petromod v11 software. Stratigraphical, paleontological (Baranyi 2016), organic-geochemical (Orbán 2013), petrophysical, paleo-water depth (Báldi & Sztanó 2000) data and radiometric ages (Lukács et al. 2014) were used in the modelling. The measure of extension of the crust and mantle for the area was taken from Horváth (2007). The aim was to unfold the subsidence history of the sub-areas, to make comparisons between them. The lgTTI/R% trend elaborated for the subbasins of the Pannonian Basin was also analysed and compared with the modelling outputs.

3. THESES

1. **11 Cenozoic deformational phases/stress field (D1-D11) were identified**
2. **D1 stress field (Late Eocene-early Egerian?):** it is characterised by NE-SW compression and perpendicular extension. The stress field is pre-tilt. NW-SE trending conjugate reverse faults and perpendicular extension structures came into being at that time. Disaggregation type deformation bands belong to this stress field indicating early syn-sediment deformation during Oligocene. Map-scale faults of D1 stress field were not

observed. This stress field can be regarded as a local one in the Pannonian Basin where the prevailing compressional direction was (W)NW-(E)SE during the Paleogene (Fodor et al. 1999, Fodor 2010).

3. **D2 phase (Paleogene-early Eggenburgian):** it is divided into two sub-phases which were identified as either Paleogene or Eggenburgian rocks. **The D2a** sub-phase indicates NW-SE compression/transpression. NE-SW trending conjugate reverse faults and NNE-SSW trending deformation bands are its typical structural elements. NNE-SSW trending west-northwest vergent blind reverse faults (Petrik et al. 2016) and oblique reverse faults (Beke 2016) came into being in the DDB area during this phase. Slightly differently oriented NE-SW trending blind and non-blind reverse faults with various vergence were identified in the Vatta-maklár Trough (VmT). Shortening basins (e.g. pre-Vatta-maklár Trough) evolved in front of the propagating blind reverse faults where hundreds of meters syntectonic wedges deposited. The evolution of shortening basins is coeval with that of the North Hungarian-South Slovakian Paleogene Basin, which was interpreted as retro-arc flexural basin (Tari et al. 1993).

The **D2b** sub-phase is a new one in the Pannonian Basin and it is characterised by NE-SW extension during Paleogene-early Eggenburgian. Pre-tilt syn-sediment dilational deformation band and conjugate normal faults belong to this phase. Map-scale faults of D2b could not be observed. The D2b sub-phase may indicate local extension, which often evolves perpendicular to the fold axes.

4. **D3 phase (middle Eggenburgian-late Eggenburgian):** this phase represents E-W compression and perpendicular extension which evolved after the first major tilt event (T1). This phase induced strike-slip deformation, which affected the Eggenburgian Pétervására Fm. their most typical elements are conjugate strike-slip faults, syn-diagenetic fractured pebbles, E-W and N-S oriented deformation bands.

The NNE-SSW trending structures still acted as reverse faults in the Darnó Deformation Belt while (E)NE-(W)SW trending dextral strike-slip faults evolved in the Vatta-maklár Trough and the southern Bükk foreland. The Mezőkövesd-, and Mezőkeresztes-bulge are located along the restraining bends and step-overs of the southern major fault (Vatta-maklár Fault, VmF) of the VmT and they are interpreted as compressional bulges. The upper Kiscellian and Egerian parts of the succession were eroded on the bulges (Majzon 1961) whose material was supposedly found in the Lower Miocene terrestrial sediments of the VmT. The evolution of dextral strike-slip faults corresponds to Early Miocene dextral movements along Mid-Hungarian Shear Zone (Csontos et al. 1992; Fodor et al. 1998).

5. **D4 phase (Ottnangian-early Karpatian):** this phase indicates N-S and NNE-SSW extension. E-W trending syn-sediment normal faults, covered faults, fractured

pebbles and deformation bands belong to this phase, which affected the lower-rhyolite tuff level. According to paleomagnetic data, the lower-rhyolite tuff shows 85-90° CCW rotation (Márton & Pécskay 1998). The D4 phase is coeval with second major tilting event, which resulted in the syntectonic thickening of Early Miocene sediments.

Some nearly E-W oriented map-scale oblique normal faults evolved in the DDB and southern Bükk foreland while the earlier NNE-SSW trending major structures were inactive.

The early syn-rift evolution of the western part of the Vatta-maklár Trough can be tied to the D4 phase when the major (E)NE-(W)SW oriented dextral faults became oblique normal faults (e.g. the western branch of the VmF). More than 500 m thick early syn-rift Ottnangian?-Karpatian sediments and lower ryholite tuff (16.5±0.3 Ma; Lukács et al. 2014) deposited in the western part of the VmT.

In contrast to the western branch of the VmF, the eastern one was inactive because its strike was parallel to the extension direction of the D4 phase. As a result, the eastern part of the Vatta-maklár Trough went through a quiescent period in terms of tectonics.

Fodor (2010) named the N-S extension as the D9a episode which went into the first major CCW rotation resulting in the cessation of dextral movements along the Mid-Hungarian Shear Zone. In my opinion, the N-S extension is not only an episode but a separate phase (D4) and the cessation of dextral movements along the Mid-Hungarian Shear Zone can be tied to the evolution of the extensional D4 phase during Ottnangian.

6. **D5 phase (late Karpatian-earliest Badenian):** this phase represents **(**E)NE-(W)SW extension and perpendicular compression which already affected the middle-dacite tuff (16.0±0.3, 16.3±0.3 Ma; Lukács et al. 2014,2015). This phase evolved after the first CCW rotation and includes some obliquely reactivated structures of the earlier E-W oriented normal faults of the D4 phase. NE-SW oriented reverse faults were also present.

During the main part of the D5 phase the NNE-SSW trending major structures in the DDB area were still inactive.

The map-scale faults of the southern Bükk foreland and VmT were also inactive because their strike were almost parallel to the extensional direction of the D5 phase. The sediment thickness does not change significantly in the VmT and at its margins in correspond to the inactivity of major faults. During the D5 phase, the throw of the VmF along its strike did not increase.

Numerous sub-basins evolved in the Pannonian basin due to NE-SW extension but the major structures of my study area seems to have been inactive.

7. **D6 phase (early Badenian-middle Sarmatian?), D7 phase (late Sarmatian?):**

Based on field observations the D6 and D7 phases can be distinguished from each other but in case of map-scale structures the separation is difficult as the difference between extensional directions is only 15-30°. Both phases affected the upper-rhyolite tuff (14.8±0.3Ma, Demjén Ignimbrite; Lukács et al. 2015) and the Sarmatian sediments and they are coeval with the third major tilt event (T3a).
The D6 phase evolved after second CCW rotation and indicates E-W extension and perpendicular compression. NW-SE dextral and NE-SW sinistral strike-slip faults, N-S trending conjugate normal faults, covered faults and deformation bands belong to this phase.
The D7 phase shows NW-SE extension and reactivates the N-S trending normal faults of the D6 phase as oblique dextral ones during late Sarmatian.
The fault pattern of the DDB is similar to that of Fodor et al. (2005) but it is more detailed especially in the area between DDB and VmT.
The fault pattern from DDB to Polgár 3D seismic block can be interpreted as a whole. In the DDB, the NNE-SSW trending faults which acted as oblique faults during the D6 are predominant (e.g. Tárkány-Fault). In the D7 phase the extensional deformation became prevalent along the NNE-SSW trending faults, which resulted in the evolution of many half-grabens (e.g. Felsőtárkány-basin).
The strike of the major structures in the Vatta-maklár Trough (VmT) and in the Polgár-Trough (Polgár 3D block) have predominantly NE-SW. The major southern boundary faults (e.g. VmF) of both troughs change their strike along their length and at their eastern terminations they turn to north-northeast direction. The southern boundary fault (VmF) of the VmT is made up of many segments which coalesced during its propagation. As opposed to the VmF, the south-eastern boundary of the Polgár-Trough is bordered by NE-SW trending segmented en-echelon faults along which many relay ramps were mapped. Right-stepping, NE-SW trending oblique faults are predominant at the northern margin of the VmT while the NNE-SSW trending en-echelon normal faults prevail in the Polgár-Trough during the D6/D7 phase.
In summary, both troughs started to evolve as strike-slip basins due to transtensional deformation at the end of Middle Miocene.
In my opinion, the VmT cannot be interpreted as strike-slip duplex (Tari 1988) but it is a transtensional pull-apart basin which are composed of many intrabasin highs and sub-basins. The eastern part of the VmT started to subside earlier than the western counterpart during the D6 phase due to the change in strike of the eastern branch of the VmF.

In Polgár 3D seismic block, a NE-SW trending Middle Miocene half-graben was also mapped which suffered inversion along its southern boundary fault during at the end of Middle Miocene-earliest Late Miocene period.

8. **D8 phase (Pannonian):** it is characterised by NNW-SSE and N-S extension. This phase is syn/post-tilt with respect to the T3b tilt event. This is a new structural phase in the Pannonian Basin. E-W oriented normal faults, deformation bands could be observed in early Late Miocene sediments.

There is no proof for the early Late Miocene activity of NNE-SSW trending faults in the DDB which can be explained by the extensional direction of D8 phase which was almost parallel to the strike of major structures.

The NE-SW trending structures in the VmT and in the Polgár-Trough acted as normal faults during the D8 phase which reshaped the VmT and the Polgár-Trough as a complex and a simple half-graben, respectively. Many fault-related folds were mapped along the major southern boundary faults of both troughs. The geometry of the folds are changing along-strike of the faults, extensional monoclines and their faulted version or simple normal drag equally developed in the downthrown fault blocks. Transverse folds were also mapped along major faults whose fold axes are mainly perpendicular to the strike of the faults. These folds indicate the variation in offset and subsidence along-strike of major faults. The extension was ~2-3% in the western and ~3-4% in the eastern part of the VmT in reference to the base Pannonian level.

NE-SW trending en-echelon faults at the northern margin of the VmF acted as normal faults while the majority of the NNE-SSW trending en-echelon faults in the Polgár-Trough became inactive during D8 phase.

9. **D9-D11 phases (Pannonian?-Quaternary):** the separation of the young Pannonian-Quaternary deformations from each other is problematic due to the scarcity of structural measurements in the rocks deposited at that time.

The D9 phase indicates NNE-SSW extension while the D10 shows NE-SW extension. Both extensional directions occurred previously (e.g.D4, D5) but the tilt test proved that these deformations return during latest Miocene-Quaternary.

The (E)NE-(W)SW trending major structures might have been active as oblique faults during the D9 phase, which is proven by the small-scale syntectonic thickening of sediments deposited in the troughs after ~9.78 Ma. The major structures are shortened along their length and some of the branches become inactive in the fluvial/deltaic sediments (e.g. western branch of the VmF).

Numerous compactional faults were mapped above the volcanic features and the extensional monoclines in the Polgár-Trough which detach onto different stratigraphic levels. These atectonic faults do not intersect the base Pannonian level.

The D11 phase is represented by NNE-SSW compression and perpendicular extension which corresponds to the recent stress-field of the area (Bada et al. 2007). E-W oriented reverse faults and conjugate strike-slip faults belong to this phase.
Some syn?/post-Pannonian shortening features were recognised in the fluvial/deltaic sediments in the VmT and in the Polgár-Trough. In the eastern part of the VmT some reversely displaced sediments and reverse dragging were observed along the earlier (E)NE-(W)SW trending normal faults. The southward tilting of the youngest fluvial/deltaic sediments and their erosional truncation to the north can be tied to the uplift of the Bükk Mts (Dunkl et al. 1994). The projection of the fluvial reflectors to the north, hundreds of meters erosion of the Pannonian strata can be estimated.

10. **Subsidence modelling:** 4 major subsidence periods corresponding to the activity of map-scale faults were distinguished in the Vatta-maklár Trough. The two most significant subsidence periods were the deposition of terrestrial sediments and lower-rhyolite tuff during Early Miocene and the other when the early Pannonian pre-deltaic strata deposited along the downthrown blocks of major normal and oblique faults.
1 main subsidence period was identified in the Polgár-Trough which started from late Middle Miocene to date. The rapid subsidence was bracketed in 11.6-9.78 Ma when 1500m thick pre-deltaic sediments deposited. This was followed by a more moderate subsidence which has been lasting to date.

11. **Shelf-margin slope position and its age:** the base of the slope and a deltaic horizon (~9.78 Ma) were also mapped in the VmT and in the Polgár-Trough to determine paleo-shelf position. In both areas the shelf-margin slope evolved before 9.78 Ma and can be found north with respect to the 8.6 Ma-aged paleo-Danube shelf-margin slope identified by Magyar et al. (2013). The progradation occured south-eastward in the VmT and south-westward in the Polgár-Trough where it was fault-controlled. North-western progradation direction was observed at some relay ramps which influenced locally the main progradation direction in the Polgár-Trough.

12. **Volcanic features in Polgár 3D seismic block:** numerous segmented/non-segmented layer-parallel or slightly saucer-shaped sills were mapped in the Polgár-Trough. The sills are found in different depth but they generally intruded ~100-800m deep from the paleo-surface. Their average length is ~1-3km, their thickness is ~50-100m. Numerous forced folds were mapped especially above shallowly emplaced sills which proved the magmatic activity in early Pannonian (~11.6-9.78 Ma), prior to the progradation of paleo-shelf slope. The intrusion/emplacement direction was either north-western or south-eastern based on the junction and segmentation points of sills, but the major fault-zones and relay ramps might have influenced it.

Besides sill, some rhomboid/eye-shaped hydrothermal vents/mounds were mapped on the paleo-surface (base Pannonian). Their average height is 300-400m. They are onlapped by pre-slope Pannonian sediments thus their age is also early Pannonian (~11.6-9.78 Ma), prior to the progradation of paleo-shelf slope. Terminating sills and faults were found just exactly below the hydrothermal mounds which may have played a key role in their evolution.
NE-SW aligned continuous volcanic belt is located south-east of the Polgár-Trough which are made up of lava domes, lava dome complexes, smaller stratovolcanoes. This area along with the volcanic features in Sajóhídvég, north of the Polgár-Trough might have been the magma source for sills.

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