STRUCTURE, METAMORPHISM, GEOCHRONOLOGY AND DEFORMATION HISTORY OF MESOZOIC FORMATIONS IN THE CENTRAL RUDABÁNYA HILLS

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Ph.D. Theses

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2012

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1. Introduction, questions and aims

My Ph.D. dissertation deals with the structural evolution of the central part of the Rudabánya Hills. The main goal of my work was suggesting a new structural model and evolution for the central part of the Rudabánya Hills. I worked on the next topics in details: (I) sedimentary features and age of the Jurassic slope and basinal, subduction-related formations in the Rudabánya Hills, (II) new definition or redefinition of the tectonic units of the Rudabánya Hills, (III) polydeformational tectonic evolution of the different nappes based on structural mapping and micro-tectonic studies, (IV) p-T conditions of the very low- to low-grade metamorphic event in different tectonic units, (V) dating of the deformation phases derived from K-Ar white mica analyses (VI) p-T conditions of the nappe movements.

To achieve these aims the main tasks were:

Defining nappes: How many nappes are present in the research area? What is their present-day position? What is the geometry of the nappe boundaries? What were the relative and absolute ages of the nappe stacking phases? Can I find some shear criteria to characterize the direction of the nappe movements? What is the present-day structural order of the nappes? How many nappe stacking phases can be distinguished?

Characterizing their lithostratigraphic content: What is the relationship between the different Triassic and Jurassic series? Is it possible to find Jurassic stratigraphic continuations of the Triassic sequences? Did all Jurassic sequences have/used to have a Triassic basement? How to distinguish the Jurassic series on field and in laboratory? What was the depositional environment for the poorly constrained Jurassic series? What is the source area of the clasts of the Jurassic olistostromes? Is it possible to find proofs on the relationship of the rhyolite and the shale in the TO complex? Is there any other method to get the sedimentary age of the poorly constrained black shale?

Describing the inner deformation (partly ductile) of the nappes: How many ductile deformation events were present in the investigated rocks? Are they present in all of the nappes or diagnostic for some of them? What is the order of the events? Is it possible suggesting any age constrain for the deformation phases? How the micro-texture look like? What are the main micro-scale deformational features? What were the main mechanisms of deformation?

Characterizing the p, T and t conditions of the metamorphism: What minimum temperature can be suggested by the above mentioned deformation mechanisms? What kind of tectonometamorphic evolution can be suggested in the investigated nappes? What was the age of the metamorphic event(s)? Is it possible to use the previously measured metamorphic petrological data, and compare them with the new results? Is it possible to distinguish nappes on basis of their metamorphic degree/history?

Characterizing the P, T and t conditions of the nappe movements: What kind of information can be squeezed out from nappe-base (nappe-sole) rauhwackes? Is it possible to find suitable syndeformational minerals for fluid inclusion studies?

Comparison: Do my observations/results suite in any of the existing models about the Mesozoic evolution of the Inner Western Carpathians? Do they suggest any changes? Do I add some new data to better understanding the Mesozoic evolution of the Neotethys Ocean?

2. Methods

Structural observations and measurements were carried out in the majority of Triassic and Jurassic outcrops in the central part of the Rudabánya Hills. Measurements included bedding, foliation and occasionally fold axes. Representative cross sections were constructed from outcrop-scale observations and reinterpretation of borehole data. A detailed, but not complete geological mapping of the key areas completed the structural observations. The main goals were to check formation boundaries, measuring dip values and to determine the bedding- foliation relationship.

Several boreholes and core sections (Szet-3, -4, Sza-4, -5, -7, -10, -12, Va-1, -2, -3, -4, P-74, Szo-3, Ha-3, -4, Rb-658, -661, Tsz-16) were reinvestigated to examine the penetrated structural/ sedimentological boundaries, and take new samples for **thermometamorphic and microtectonic studies**. The relationship of the Upper Triassic and Jurassic series was the target of special interest, because it has crucial importance in the evaluation of stratigraphic and tectonic problems.

For microstructural investigations oriented thin sections were prepared from rock slabs cut perpendicular to the foliation planes. The usual lack of lineation prevented the preparation of thin sections along X-Z fabric planes.

Rock samples were selected for new metamorphic petrologic studies. Almost two hundred illite Kübler index (KI), chlorite "crystallinity" (ChC) and K-white mica b cell dimension data were elucidated in order to separate the different nappes and characterize the temperature and pressure conditions of the metamorphic event(s). Part of the data was measured more than 20 years ago by the same laboratory and team (Árkai & Kovács 1986, Kovács & Árkai 1989, Árkai 1981, 1985, 1989). Thus it became possible to compile a comparable database of the earlier and recent data in this study.

To constrain the timing of the detected very low to low-grade metamorphism **K-Ar age data** were measured on <2μm grain size fractions from 10 samples on which metamorphic petrological samples investigations had been carried out.

Samples were collected from rhyolite bodies of the Telekesoldal complex (TO) to carry out **U/Pb dating**. The specimens had different position in comparison with the Jurassic shale matrix: 100 m size body, few cm-sized olistoliths from the olistostrome horizons, volcanoclastic material from the matrix of the olistostrome.

Paleostress reconstructions from the measured fault-slip data were carried out by the software of Angelier (1984, 1990). Stress axes were calculated by the Tensor module of the software. Automatic phase separation was carried out for sites, where multiple faulting phases were suspected. Automatic separation was sometimes complemented by manual separation. The software of Angelier (1984) was also used for visualisation of ductile structural data, like foliation, shear bands, lineation. Fold axes for kinks, and other type folds were estimated visually on the stereograms. In this case, the shortening direction for folds was also estimated.

Basal tectonic breccias (rauhwacke) were collected from 5 different contact zones to characterize the temperature and pressure conditions of the nappe emplacements. Synkinematic minerals from these samples were separated for **fluid inclusion studies**. These inclusions provided valuable information about the composition and the temperature of the fluids which lubricated the bases of the nappes during the tectonic processes. Pressure conditions could also be estimated. These data had a great importance during tectonic reconstructions and interpretation of the metamorphic petrological data.

3. Results

I reinterpreted the structural geometry, stratigraphical content, and stacking order of structural units in the central part of Rudabánya Hills on basis of newly obtained metamorphic petrological, micro- and mesotectonical, geochronological, sedimentological and micropaleontological data. As a result of my work the following structural units are defined in the study area.

New definition of the investigated structural units

Aggtelek nappe: The Aggtelek nappe is built up by the formations of the Silice facies unit in sense of Kovács (1989). This nappe occupies the uppermost structural position in the Aggtelek Hills. The nappe is part of the Silice nappe system but I restrict the use of the term to a tectonic nappe found in the Aggtelek Karst area.

(1) ***Henc unit***: In my definition, this structural unit is built up by different Triassic lithologies. At present it forms relatively intact **tectonic slices within the tectonic contact zone of the Aggtelek and Telekesoldal nappes**. Rocks of this unit were already shown separately on the map of Less (1998) at the base of the Aggtelek nappe, but were interpreted as strike-slip duplexes.

(2) ***Telekesoldal nappe***: I define it as **an individual structural unit, a nappe**, below which the tectonically truncated lenses of the Torna series (D_1 contact); otherwise the Bódva series (D_4 contact) can be found (Kövér et al. 2009b). The geometry of the nappe boundary is mostly the same as the boundary of the TO complex on the geological map of Less et al. (1988). I suggest the following differences. A) in the borehole Szendrő Szet-4 I classify the uppermost, shale and marl part of the core to the Telekesvölgy complex (TV), against the original classification into the TO complex (Less et al 1988). B) in the surrounding of the borehole Szalonna Sza-5 according to my opinion the non-metamorphosed marls of the TV complex crops out which is different from the previous concepts (Less et al 1988). The basal D_4 thrust surfaces of the TO nappe may have been reactivated or deformed several times (e.g. in phase D_5) after the main nappe emplacement, so they certainly do not reflect the original structural geometry.

(3) I pointed out, that the **TO complex, the Akasztó unit, the Nyúlkertlápa beds and the Hidvégardó series** show very similar early deformation history (D_1-D_3) and well-pronounced high-temperature anchizonal to epizonal metamorphism (Árkai & Kovács 1986, Kövér et al. 2009a, b). Their lithological characteristics are also similar (black slates, silicified or marly slates, sandstone turbidites, olistostromes). Reassessment of the radiolarian fauna from borehole Szendrő Szet-3 refined the age of the classical TO complex to Bajocian (Kövér et al. 2009c). First findings of marine palynomorphs in the Rudabánya Hills evidenced Bajocian-Callovian age for the classical part of the TO complex, and Bajocian age for Akasztó unit (Kövér et al. 2009c), which is in contrast with its classical Lower Triassic classification (Less et al. 1988). I suggest that these units were derived from the **same sedimentary complex**, the now enlarged TO complex. At present, the TO complex forms different nappe outliers of the same Telekesoldal nappe.

(4) According to the new sedimentological investigations, the TO complex represents a subduction-related complex, composed of black shales, sandstone turbidites and olistostrome horizons, deposited by gravity mass flows (Kövér et al. 2009c, Haas et al. 2011). Previous conception about separating the shale, sandstone olistolith, limestone olistolith and rhyolite lithofacies units in stratigraphic level and time (Grill 1988) is completely modified.

The sandstone forms layers within the shale. Present-day lens-shaped occurrence of the **sandstone is the result of extensional shear zones and formation of boudins** in D_4 or D_{5b} deformation phase. **Sandstone, micro-olistostrome and coarse-grained olistostrome layers are present in every stratigraphic level**, and they do not show any kind of age distribution.

(5) The **rhyolites are not** coeval subvolcanic bodies, but **forms olistoliths**. I proved Late Triassic volcanic age of the rhyolite by new U-Pb radiometric data concentrating around two ages: **220 and 206 Ma**.

Torna series**:** My new observations strengthen the conclusion of Less et al. (1988), Less (2000) and Fodor & Koroknai (2000) that the Torna series incorporates diverse Triassic successions, which were formed on different paleogeographic position on the attenuated continental crust.

(6) ***Bódva series***: Structural units built up by the formations of this series are present in the Rudabánya Hills in two structural positions due to multiple nappe stacking events. It represents the lowermost known structural unit south from the Bódva River, where it was thrust over by the Telekesoldal nappe, the Henc unit and the Aggtelek nappe during D_4 nappe stacking event. Juxtaposition of the metamorphosed TO nappe and the Bódva nappe surely postdates the very-low to low-grade metamorphic event, while the latter unit is proved to be suffered only diagenetic alteration (Árkai & Kovács 1986, Kövér et al. 2009a, b). This metamorphic on non-metamorphic nappe pile was reorganised by southward-verging thrusts in D_5 phase, resulted in thrust of Bódva series over the TO complex along the Szalonna thrust (Szentpétery & Less 2006) in the Bódva gorge area.

Lithologically, the Bódva series is built up by formations of the Triassic Bódva facies unit in the sense of Kovács (1989). However, new observations and reinterpretation of several borehole data let expand the sedimentary age of the Bódva series into the Jurassic. According to my new interpretation, the Norian Hallstatt Limestone of the Bódva series gets more argillaceous upward and gradually progresses into red to green and then grey marl (Kövér et al. 2008, 2009c). Its Norian-Rhaetian age was proven by foraminifers (Kövér et al. 2009c). This variegated marl builds up the lowermost part of the TV complex. It progresses into grey marl and calcareous marl, containing significant amounts of redeposited crinoid fragments. The uppermost lithofacies unit of the TV is black shale, rich in radiolarians and sponge spicules. It is a typical deep pelagic basin facies, Bajocian to Early Bathonian in age, according to the revised radiolarian fauna (Kövér et al. 2009b). In summary, I suggested, that the **TV complex is the original sedimentary cover of the Lower Triassic–Norian Bódva series**.

Milestones of the deformation

(7) *D_1 deformation phase*

I pointed out that post-sedimentary deformation of the enlarged TO complex (including the NL beds, Jurassic rocks of the Akasztó unit, and probably the Hidvégardó series) and the Torna series started with a tectonic burial due to nappe stacking. Estimated p-T conditions on basis of illite Kübler index (KI), chlorite "crystallinity" (ChC) and K-white mica b cell dimension data are 1.5-2.5 kbar and 300-350°C for the TO nappe, and 3-4.5 kbar and 300-350°C for the Torna series, corresponding to 5–15 km burial (Kövér et al. 2009a,b).

This tectonic burial resulted in S_{0-1} foliation in both tectonic units. At outcrop-scale a closely-spaced (millimetre-scale), penetrative foliation (S_1) is the most characteristic structural feature of this phase. This foliation is equally present in the slate, siltstone, sandstone and olistostrome horizons. In map view, the general moderate NW (in average: 320/40) dipping of the S_1 foliation can locally change into steep, almost vertical position, or alternate with steep, SE dipping segments (Dunnatető Hill, Szalonna-Perkupa road cut section), indicating later (D_4, D_5) folding phases. The closely-spaced (millimetre-scale), penetrative foliation is well developed in the slate. The foliation planes are rich in flakes of white mica. When the sample contains a considerable amount of carbonate or being silicified the foliation is less developed. In some samples the original sedimentary alteration of marl, siltstone and shale is visible. The bedding or sedimentary lamination is parallel with the well-developed foliation, thus this schistosity refers to S_{0-1}.

The fabric of the olistostrome is also characterized by layer-perpendicular flattening. In the grain-supported olistostromes stylolitic contact and oriented position of the clasts are also well visible. In case of the matrix-supported type anastomosing foliation planes wrap the flattened clasts. Some evidences for intracrystalline deformation are present. Undulate extinction of the quartz grains is common. In some grains the recovery has achieved the last phase: subgrain boundaries separate the neighbour crystal fragments, which are slightly disoriented with respect to each. No macroscopic or microscopic folding was observed to be associated with S_{0-1} foliation. In all units, S_{0-1} foliation represents the only structural feature of D_1 deformation phase.

As the result of the metamorphic petrologic studies both the TO nappe and the Torna series turned to be metamorphosed under 300–350°C, although the Torna series significantly have lower IC values. The main difference in their metamorphism is the pressure values. The b0 values suggest transitional medium/high pressure conditions (3-4.5 kbar) for the **Torna series**, while a lower, 1.5-3 kbar for the **Telekesoldal nappe**. Because of their very similar early deformational history (D_1-D_3) and metamorphic degree, I suppose, that **their tectonic contact is a very early, pre-metamorphic nappe contact**. This contact is preserved more or less intact in the Bódvarákó window, between the thin Bódvarákó series (Torna) and the tectonically overlying NL beds.

I suggest interpretation of newly obtained K-Ar ages would put a time constraint of ca. **142 – 113 Ma** (earliest Cretaceous) **for D_1 phase**. The beginning of this time range indicate the oldest possible time for the low-grade metamorphic alteration, while the younger end of the time period may reflect partial resetting of the K-Ar system due to low-temperature fluid movements connected to a later nappe stacking phase.

(8) ***D_2 deformation phase***

In the outcrops and cores of the TO nappe and the Hidvégardó series small-scale, relatively close folds are present. They bend the S_{0-1} foliation planes, thus they represent a later, D_2 folding event with F_2 folds. The geometry of these F_2 folds are few mm to few cm-scale close to tight folds. Their hinges are rounded and the limbs are straight. Most of the F_2 folds are similar folds with thickened hinges. The limbs can be extremely thinned; sometimes the hinges are completely sheared off from their limbs, forming rootless folds. In some thin sections only two different foliations are present, intersecting each other at a small angle. The original sedimentary alternation of silty, sandy or marly layers defines the S_{0-1} foliation, while the crosscutting foliation is the S_2 one.

From map-scale structures possibly the large, locally overturned and recumbent folds of the metamorphosed Torna series corresponds to this phase. Its overturned position was proved biostratigraphyically and structurally in few places in the NE Rudabánya Hills (near Ha-3 borehole and Hidvégardó, Kovács & Árkai 1989, Fodor & Koroknai 2003).

(9) ***D_3 deformation phase***

The TO and Torna rocks were later exhumed to very shallow depth, close or at the bottom of non-metamorphosed Bódva series and its evaporitic sole. The exhumation was probably associated with kink-style folding at the transition of ductile and brittle deformation fields (D_3 phase in the TO nappe and Torna series). Measured kink axes and pre-tilt reverse and thrust faults indicate NE-SW shortening for this D_3 event.

(10) ***D_4 deformation phase***

Several arguments of my structural and metamorphic petrological analyse demonstrates that the metamorphosed, deformed and exhumed TO and Torna rocks were emplaced onto the non-metamorphic Bódva series (D_4 phase). Outcrop- and map-scale structures refer to NW-SE compressional stress field (shortening) and southeast-vergent nappe emplacement, although the earlier model of Less (Less 2000) envisaged northwest-ward displacement of the Martonyi nappe (Torna series) over the Bódva series. The other metamorphic unit, the Torna series also participated in this phase, and formed a tectonically truncated nappe on the base of the TO nappe. On the northern part of the investigated area, it emplaced onto the non-metamorphosed Bódva unit. This is the case for Martonyi nappe, which is over the Bódva series, as mapped already by Less et al. (1988), published by Less (1998, 2000) and modified by Fodor & Koroknai (2000). A small klippe of Torna unit is also present in the same tectonic position on the Dunnatető Hill (Kövér 2005). More to the south, in the Telekes valley, only smaller-scale, tectonically truncated slices are preserved between the overriding TO nappe and the Bódva series. South-eastward thrusting of the Aggtelek nappe also took place in this D_4 phase. Several tectonic slices of different units were involved in the basal tectonic zone; this is marked mainly by evaporitic melange in the north, and thick rauhwacke in the south. The evaporitic melange incorporates lenses of basic and ultrabasic rocks of the Triassic oceanic crust. Lower to Upper Triassic slices of the Henc unit are present as relatively intact tectonic lenses within the basal rauhwacke.

(11) ***D_5 deformation phase***

My mapping and structural analyses suggest that the metamorphosed over non-metamorphosed tectonic couplet was thrust again onto the metamorphic TO nappe along an E-W striking thrust in the Bódva gorge (D_5 phase, Szalonna thrust of Szentpétery & Less 2006). Thrusting associated with reworking of the previous nappe contacts and map-scale F_5 folding. This folding bended the basal D_4 thrust of the TO and the Martonyi nappe, and also the overthrusting Bódva series. Fold vergency of this deformation phase indicates southward tectonic transport. This was recognised by earlier workers and correctly figured on maps (Less et al. 1988, Less & Mello 2004, Péró et al. 2003). However, they tempted to relate this late event to the early nappe stacking. On the other hand, Grill et al. (1984) and Less (2000) considered the D_4 phase overthrusting of the Martonyi nappe as Miocene in age. However, the newly measured two K-Ar ages around 90-91 Ma can tentatively be connected to any of the **D_4-D_5 phases**.

(12) My research on the basal cataclastic breccias of the overthrusting units permits to establish a relative chronology of D4 and D5 thrust contacts and the p-T data of the movements. These contact zones are characterized by tectonic rauhwackes, which preserve newly-formed minerals grown from the circulating fluids during nappe emplacement. Trapped fluids in synkinematic minerals indicated temperature up to **200-320°C and pressure up to 3.6 kbar during the D_4 nappe movements**. Hot fluids most probably derived from the metamorphic units. Fluid inclusions from the **D_5 contact** resulted in significantly lower p-T values (**200-260°C, 0.3-1.0 kbar**), indicating thrusts in shallower crustal level.

Migrating high temperature fluids along the nappe contacts caused systematic alteration in the investigated clay minerals, and highly influenced the KI and ÁI measurements. These hot fluids could partly, or totally reset the K-Ar isotope system, thus I suggest, that the measured **~90 Ma** (87–94 Ma within error bars) **is connected to nappe movements**.

The D_4 –D_5 phases obliterated the relative order of the primary D_1 or earlier nappe stack. It is probably these deformation events which led to confusions and controversial views on the position of the different structural units. Tectonic units built up by the metamorphosed Triassic Torna series and Jurassic TO nappe can be located either above or below the different suites of the Bódva series and these suggested positions are probably not due to misunderstanding the structural geometry but to real complications of the D_4 and D_5 phases. A notable extensional deformation, D_{5b} was probably connected to the D_5 phase: it appears in the now underthrusting TO unit, and may reflect the vertical loading of the overthrusting Bódva unit. Observed features are extensional shear zones, deformation bands and normal faults. The resulted extension is perpendicular to the inferred south-vergent thrust motion.

4. Conclusions: geodynamic implication

(13) My investigations strongly support that in the Middle Jurassic, subduction-related basin can be supposed for the depositional area of the shales, sandstones and olistostromes of the Telekesoldal nappe, as part of the Meliata nappe system. We have evidence for Bajocian-Callovian sedimentary age (~160- 170 Ma) (Kövér et al. 2009c). Basalt clasts of the Meliata and TO units, which derived from the oceanic crust of the Neotethys Ocean could originated from the upper oceanic plate of the ongoing intra-oceanic subduction.

The Triassic pelagic limestone, marl and shale clasts might have originated from the cover of the attenuated continental crust, from which thin slices were detached, thrust onto the West Carpathian continental margin, and formed an imbricate wedge with slightly elevated topography. This thrusting concerned only the uppermost, Mesozoic part of the crust indicated by the clast composition. Such small imbricate structures could be the source to the southerly (and not northerly) located TO complex and Meliata accretionary wedge.

(14) Opening of the Penninic Ocean far to the west in Jurassic time lead to sinistral strike slip movements, and reorganisation of the westernmost part of the Neotethyan oceanic realm (Schmid et al. 2008, Stüwe & Schuster 2010). My suggestion is that these movements may transport thinned continental fragments deriving from the NW margin of the Neotethys system far to the E, to the investigated area. This would be the event which brings the Silice nappe system in the model section. The Silice nappe system could be in contact with the Meliata accretionary wedge, at least partly overthrusting it. This is the explanation why the basal evaporitic sole of the Silice nappes contains blocks from the obducted ophiolite pile.

(15) Coeval and slightly post-dating this strike-slip event, in the early Cretaceous, subduction of the deeper continental crust of the West Carpathian margin continued. The uppermost, Mesozoic part of the thinned and already imbricated crust also entered the subduction zone, indicated by the medium-pressure metamorphism of the Torna structural unit. Part of the Jurassic Meliata/TO sediments submerged into the subduction zone, too. This is the time (D_1) when the Torna structural unit underplates the tectonically buried Meliata sedimentary melange. Meanwhile, part of the already HP metamorphosed oceanic and continental crustal fragments (Bôrka nappe) completed their ascent in the subduction channel. This exhumation took place up to the foot of the buried Meliata sedimentary melange. Ongoing compression pushed tectonic slices of the HP unit into the Meliata unit as a tectonic matrix. From this point, it is not only a sedimentary, but also a tectonic melange, containing slices of the exhumed HP Bôrka nappe. In summary, the Torna–Meliata–Bôrka structural units get in contact in this relatively early time (~140 Ma). Low-grade prograde metamorphism of the Torna and Meliata tectonic units and retrograde metamorphism of the Bôrka HP nappe were coeval, indicated by K-Ar data (140-120 Ma; Árkai et al. 2003, and the present study). Position of the Bôrka HP nappe in the Meliata melange as a tectonic "matrix" can explain its controversial tectonic position, situating either below or within the lower-grade Meliata nappe sensu stricto.

The mid-Cretaceous Eoalpine phase resulted in both thick-skinned and thin-skinned nappe movements in the Western Carpathians, too. In the Silice – Meliata –Torna domain, the time period from ca. 115 up to 90 Ma correspond to major post-metamorphic nappe emplacements, which is testified by D_4 and D_5 phases in the Rudabánya Hills. Thin-skinned nappes of the Silice nappe system were thrust over large distances along layers of fluid-overpressured cataclastic mush (rauhwacke). Among them, one of the final events could be the juxtaposition of the Muráň nappe (Silice nappe system) with the Vepor nappe, whose basal rauhwacke were dated as ~85 Ma (Milovský & Plašienka 2007). Reorganisation of the slices of the exhumed Meliata, Torna/Turňa and Bôrka nappes took place during these D_4 and particularly D_5 phases. These are the phases during which the Torna unit thrust over the Meliata sensu lato (formerly Hidvégardó series) in the northern Rudabánya Hills. This is why the Turňa nappe in Slovakia frequently positioned just below the Silice nappe. These late-stage nappe emplacement dominate the present tectonic structure of the Inner Western Carpathians. They are largely responsible for the former contradictory views on the structure of the Aggtelek–Gemer–Rudabánya area.

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