Structural evolution of the Turňa Unit constrained by fold and cleavage analyses and its consequences for the regional tectonic models of the Western Carpathians

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(Manuscript received September 16, 2015; accepted in revised form March 10, 2016)

Abstract: The Turňa Unit (Turnaicum, Tornaicum) is one of the three nappe systems involved in the geological structure of the inner zones of the Western Carpathians. The unit is formed by a system of partial nappes and duplexes, which overlie the Meliata Unit s.l. and are overridden by the Silica Nappe. The Slovenská skala partial nappe in the investigated area includes clastic sediments of the mid-Carboniferous, Permian and Early Triassic age, followed by mostly deep-water Middle—Upper Triassic succession predominantly composed of carbonates. Structural analysis of cleavage planes and folds was carried out predominantly in the Lower Triassic Werfen Formation. The measured deformational structures are polygenetic and were principally formed in three successive deformation stages. The first deformation stage is represented by bedding-parallel, very low-grade metamorphic foliation that was related to nappe stacking and formation of the Mesozoic accretionary wedge during the latest Jurassic and earliest Cretaceous. The second deformation stage is represented by systems of open to closed, partly asymmetric folds with SW–NE oriented, steeply NW- or SE-dipping axial-plane cleavage. Regionally, the folded bedding planes are usually moderately SE-ward dipping, the NW-ward and subvertical dips are less common. The mesoscopic fold structures predominantly occur in the SW–NE trending anticlinal and synclinal hinge zones of large-scale folds. These structures evolved in a compressional tectonic regime with the NW–SE to N–S orientation of the maximum compressional axis. The third observed deformation stage was activated during ENE–WSW oriented shortening. This stage is chiefly represented by open, kink-type folds. Some inferences for regional structures and tectonic evolution of the area are discussed as well.

Key words: Western Carpathians, Turňa Unit, Slovenská skala partial nappe, structural analysis, folds, cleavages, tectonic model.

Introduction

The Western Carpathians represent the Alpine collisional belt that is conventionally subdivided into the External, Central, and Internal Western Carpathians (EWC, CWC and IWC, respectively — see e.g., Plašienka et al. 1997; Froitzheim et al. 2008). In principle, the EWC (so-called Flysch Belt) represent the outer accretionary wedge of the Carpathian orogen formed in response to the Eocene to Middle Miocene subduction of an oceanic basin connected to the Northern Penninic zone (Valais-Rhodanubian-Magura Ocean, or “Carpathian embayment” — e.g., Schmid et al. 2008). The EWC are separated from the CWC by a narrow zone with an intricate structure known as the Pieniny Klippen Belt that includes several units derived from the Middle and Southern Penninic zones stacked and later laterally dispersed during the latest Jurassic and earliest Cretaceous. The CWC, as a counterpart of the Austroalpine nappe system of the Eastern Alps, is composed of three crustal-scale thick-skinned thrust sheets (the Tatraic, Veporic and Genetic) from bottom to top and three large-scale cover nappe systems (Patric, Hronic and Silicic) which were all individualized and stacked during the late Early and early Late Cretaceous Palaeoalpine (ca 120–90 Ma) orogenic processes (Plašienka et al. 1997). The southern CWC zones (Vepor-Gemer area) are closely linked to the outer IWC units, namely to the Meliatic-Turnaic-Silicic nappe pile. These nappe units are interpreted as being closely related to the Middle Triassic opening and Late Jurassic closure of the north-western branch of the Neotethys (Meliata Ocean pro parte), along with the other units exhibiting evolutionary trends similar to the Southern Alpine and Dinaridic domains (Transdanubian and Bükk units, respectively), which occur to the north-west of the Mid-Hungarian Shear Zone (e.g., Kovács 1992; Kovács et al. 2011).

Nevertheless, there are still many uncertainties concerning the original palaeogeographic position of some rootless allochthonous thrust sheets like the Turňa or Silica nappes, owing to their ambiguous or even opposing structural versus palaeogeographical links. For instance, assuming the general northward progradation of the Western Carpathian orogen, the structural superposition of Silica over Turňa over Meliata units and some north-vergent thrust-sense criteria would indicate the original palinspastic position of the Turňa and Silica nappes south of the Meliata Ocean (Grill et al. 1984; Hók et al. 1995; Rakús 1996; Lexa et al. 2003; Csontos & Vörös 2004; Dallmeyer et al. 2008). On the contrary, facies relationships of especially the Middle–Late Triassic complexes apparently point to the “northern” shelf-slope settings of these units (e.g., Mandl 2000; Gaál 2008;
Schmid et al. 2008; Gawlick et al. 2012). Even a combined view was presented by Grill et al. (1984), Kozur (1991), Kozur & Mock (1997), Less (2000), Kovács (1992, 1997) and Kovács et al. (1989), whereby the Turňa (Torna in Hungarian terminology) and similar units in the Rudábánya Hills of north-eastern Hungary were placed on the southern, whereas the Silica (Aggtelek) Nappe was on the northern Meliata margin. These contradictory views evidently call for new data that would clarify at least the most uncertain points of the Meliata-related puzzle.

Our contribution concerns the structural pattern and tectonic evolution of one problematic fragment of this ambiguous interpreted tectonic system — the Slovenská skala partial nappe, which is interpreted at present as an element of the Turnaic thrust sheet occurring in the western part of the Slovak Karst Mts. and surrounding areas (Fig. 1). Thus the aim of this paper is to describe the principal mesoscopic deformation structures recorded in the Turnaic Slovenská skala partial nappe, especially fold and cleavage systems, and to interpret their relationships to macrostructures as clues for deciphering the nappe stacking processes and structural history of the area.

Geological setting and composition of the Turňa Unit

The Torna Unit as an independent tectonic unit composed of slightly metamorphosed, mostly deep-marine Middle–Upper Triassic limestones and shales, was first distinguished in the Rudábánya Mts. of north-eastern Hungary (e.g., Grill et al. 1984). In Slovakia, the term Turnaicum (Tornaicum) was introduced by Vozárová & Vozár (1992) for the unit encountered in the upper 600 metres of the BRU-1 borehole drilled in the core of the Brusník anticline (see Fig. 2). The lower unit in this borehole is formed by olistostromes, shales and radiolarites dated as Jurassic (Ondrejičková 1992) and correlated with the Meliata Unit. The upper unit is composed of a continuous succession of Upper Palaeozoic and Triassic sediments of special composition differing from both the Silica Nappe that crops out south of the Brusník anticline, as well as from the underlying Jurassic complexes. Therefore the Turniaicum was distinguished as an independent nappe unit of higher order, analogously as the Meliaticum and Silicicum (see also Mello et al. 1997). In former times, rock complexes of the Turnaicum in Slovak territory, together with the presently used terms Meliaticum and Silicicum, were considered to be either a constituent of the “South Gemic Mesozoic” cover of the Gemic basement (e.g., Bystricky 1964), or a part of the Silica Unit after the Meliata Unit and Silica Nappe were differentiated (Kozur & Mock 1973; Vass et al. 1986).

The Turnaicum is composed of several partial nappe (Slovenská skala partial nappe in the investigated area, Turňa Nappe s.s. in the eastern part of the Slovak Karst Mts.), which overthrust the Meliata Unit (Meliaticum) and are overridden by the Silica Nappe (Silicicum). However, some differing interpretations of the tectonic position of the Tornaic complexes have been proposed in Hungary. For instance, the Martonyi Unit in the Rudábánya Mts. overthrusts the Silicic Bödva Unit (Less 2000; Fodor & Koroknai 2000) and is overridden by the Meliatic Telekesoldal Unit (Kövér et al. 2009; Deák-Kövér 2012; Kövér & Fodor 2014). Obviously this area was affected by several out-of-sequence thrusting events and interpretation of the structural positions, as well as of the palaeogeographic settings of various partial units remains controversial. This problem can only be resolved by further detailed investigations in both southern Slovakia and northern Hungary, jointly by researchers from both countries. Our study area only concerns a piece of this puzzle and covers the Slovenská skala partial nappe south of town Jelšava (Figs. 1 and 2).

In order to decrease the number of local names with various meanings to a minimum, we shall treat the terms Turňa (Turnaicum), Torna (Tornaicum) and its various partial nappes as synonyms of the reduced term Turňa Unit, which will be used throughout the following text.

Treated in this way, the Turňa Unit outcrops predominantly in the southern part of the Slovenské rudohorie, Revúcká vrchovina and Slovenský kras Mts. in south-eastern Slovakia and also in the Rudábánya Mts. in north-eastern Hungary. The south-eastern boundary of surface occurrences of the Turňa Unit is formed by the SE branch of the Darnó Fault (e.g., Fodor & Koroknai 2000), but its possible continuation to the east and west is unknown due to burial by a thick cover of overstepping Oligocene and Neogene sediments.

In general, the Turňa Unit embraces clastic and carbonate deposits of the Carboniferous to Late Triassic age with a possible, but yet undocumented extension into the Jurassic (Fig. 1). The mid-Carboniferous (early Pennsylvanian–Bashkirian) Turiec Fm. is composed of very low-grade, deep-marine “flysch” deposits including dark pelagic shales and silicites (lydites), turbiditic sandstones, acidic volcanoclastic intercalations and bodies of carbonate olistostromes (Vozárová & Vozár 1992). Overlying Permian continental red-bed-type clastic strata (Brusník Fm.) were deposited after a considerable time gap and consist of variegated shales, siltstones, sandstones and conglomerates arranged in several alluvial cycles. Some evaporites like gypsum were deposited around the Permian/Triassic boundary (drilled by the Držkovce DRŽ-1 borehole — Mello et al. 1994; cf. Fig. 2, cross-section A).

The Lower Triassic strata are represented by the clastics-dominated Werfen Formation, which is the most widespread sedimentary complex of the investigated area, reaching the thickness of more than 500 metres. According to Mello et al. (1997, 2008), the Werfen Fm. is represented by the Bödva–sžilas Member (originally defined as a formation by Hips 1996) composed of variegated sandstones and shales over-
TURňA UNIT EVOLUTION AMIDST W. CARPATHIAN REGIONAL TECTONIC MODELS

1. Quaternary deposits
2. Neogene volcanics
3. Miocene sediments of the Southern Slovak Basin
4. Silica Unit
5. TURňA Unit
6. Meliata Unit a.) reinterpreted part
7a. Gomer Unit - Upper Palaeozoic and Mesozoic formations
7b. Gomer Unit - Ochtiná Group
7c. Gomer Unit - Gelnica Group
8a. Vepor Unit - Upper Palaeozoic formations
8b. Vepor Unit - Mesozoic formations
8c. Vepor Unit - Crystalline complexes

Tectonic boundaries a.) main overthrusts, b.) unspecified faults

Turňa Unit (Slovenská skala Nappe)

LEGEND

1. Turiec Formation
2. Brusnik Formation
3. Perkupá evaporite Formation
4. Werfen Formation - Bődvaszilas Member
5. Werfen Formation - Szin Member
6. Gutenberg Formation
7. Honce Limestone
8. Reilffing Limestone
8a. Nádaska and Reilffing limestones
8b. carbonate breccias and radiolarites
9. dark-grey shales - Dvorníky Beds
10. dark cherty limestone
11. Potschen Limestone
12. Hallstatt Limestone

Bratislava

study area

LEGEND

pelagic limestones
dark-grey micritic cherty limestones
dark cherty limestones
shales
carbonate breccias and radiolarites
cherty limestones
dark thick-bedded limestones
pale crystalline massive limestones
dolomites
marl crystalline massive limestones
shales and limestones
sandstones and shales
evaporites
volcanic rocks
shales, sandstones
conglomerates
sandstones
phyllites, sandstones, siltstones, cherts
carbonate olistostrome
redeposited tuffs
paraconglomerates, siltstones, lydites, rock debris
lain by calcareous shales, marlstones, sandy limestones and dolostones of the Szin Member. Sediments of the Werfen Fm. are interpreted as continental to shallow-marine, red-bed-type deposits of the supratidal flats and storm-dominated inner-lagoon (Hips 1996). The thick early Lower Triassic sandstone-shale succession of the studied area often exhibits features of turbiditic and/or tempestitic sedimentation (graded and convolute bedding, load casts) and slumping textures indicating a rather more deep-water environment probably on the outer ramp. The Szin marlstones indicate decreasing terrigenous siliciclastic supply and deposition on the outer distal ramp below the storm wave base (Hips 1996).

The Middle–Upper Triassic succession is dominated by deep marine carbonates and shales and their stratigraphy is almost exclusively based on conodonts (summarized in Mello et al. 1997). Yet the lower Anisian part is still shallow marine, composed of dark limestones and dolomites of the Gutenstein Fm., and light massive marbles of the Steinalm (Honce) Fm., but starting from the Pelsonian rifting event all younger strata are of the deep-water pelagic facies (Fig. 1). These include locally red and pink nodular and cherty limestones (Nádaska and Žarnov limestones of the Schreyeralm facies) and siliceous shales and marls in the lower part, but predominantly dark grey nodular marly limestones with cherts of the Middle Triassic Reifling and Upper Triassic Pötschen fms., intercalated most probably Camian, Reingraben-type dark shales (Dvorníky and Tomasszentandrás fms.). However, this sedimentary succession is not uniformly developed at all localities, since considerable lateral thickness, lithological and probably also stratigraphic variations occur in various parts of the Turňa Unit. For instance, the grey Pötschen limestone is replaced by the reddish Hallstatt-type limestone upsection in the Sása syncline (Fig. 1).

Methods

Structural investigations were carried out by the classic, field-based methods of structural analysis. The fundamental structural elements (bedding, cleavage, folds) were measured during the fieldwork. Meso-scale folds were preferably used for analysis of the fold orientation, along with bedding attitudes in limbs in large-scale folds. The deformation regime operating during folding was determined using the orientation data of bedding planes, fold axes and axial planes, since these largely reflect orientation of the principal shortening direction, being generally perpendicular to the maximum compression axis in simply folded regions. Fold axes and axial planes were constructed from measured fold limbs using the π pole method (construction of β axes), or by direct measuring of fold axes at outcrops (e.g., Ramsay & Huber 1987). Fold orientation and statistics were computed and visualized with the TectonicsFP version 1.7.7 software (Ortner et al. 2002). Cleavages and bedding planes are shown by rose and pole diagrams, the fold axes are plotted as points and the computed axial planes are visualized as great circles.

Cleavage is a type of planar structure in rocks that develops as a result of deformation and metamorphism and is superimposed on the primary bedding-parallel foliation in sedimentary rocks. It predominantly forms in fine-grained rocks affected by pressure solution and is approximately parallel to the XY plane of the finite strain. If the cleavage displays a geometric relationship with the fold axial planes, it is referred to as axial plane cleavage.

Field structural investigations were carried out throughout the area of the Slovenská skala partial nappe. The western part of the study area, especially steep slopes of the Blžská dolina and Drienocká dolina valleys, provided a number of good outcrops for fold and cleavage analyses. There, the structural measurements were mostly performed in the western and northern parts of the investigated area in the surroundings of the settlements of Hrušovo, Striežovce, Potok, Lipovec, Rovné, Rákôš, Nandráž, Rákonov, Kameňany, Držkovce, Sása and Jeľava (see Fig. 2). On the contrary, the structural investigations were hampered in the south-eastern part, due to the less expressive morphology and absence of sharply incised valleys. Altogether 176 outcrops were analysed and documented during the fieldworks and in total 272 bedding planes, 92 cleavage planes, 53 measured and constructed fold axes and 46 fold axial planes have been recorded and used for the structural analysis.

The well-developed and preserved folds and cleavages were observed predominantly in the Lower Triassic siliciclastic deposits of the Bodvaszilás and marly Szin members of the Werfen Fm. Alternation of layers with different rheological properties (competent vs. incompetent) resulted in comparatively rich structural record in the Werfen Fm. On the other hand, the competent and mostly massive Middle and Upper Triassic carbonates usually did not provide good exposures for the mesoscopic structural analyses.

Results of mesoscopic structural analysis

On the basis of structural analysis, a heterogeneous group of measured structures was identified. Geometry and overprinting criteria of cleavages and folds indicate the presence of three main deformational stages, in addition to synsedimentary structures. The first observed deformation is characterized by discrete S0 foliation, which is subparallel to the primary S0 bedding. The second structural paragenesis consists of folds and cleavages that developed in a compressional tectonic regime with orientation of the principal shortening axis in the NW–SE to N–S direction. In contrast, the third deformational phase was activated during the compressional tectonic regime with the ENE–WSW orientation of the main compression.

Fig. 2. Tectonic map and cross-sections showing the principal map-scale structures of the investigated area: 1 — Brusník anticline; synclines: 2 — Striežovce, 3 — Rybník, 4 — Sása, 5 — Potok, 6 — Tri peniažky-Slovenská skala.
Pre-tectonic structures

The pre-tectonic, synsedimentary and soft-sediment deformation structures were recorded in the Bôdvaszilas Member with regularly alternating sandstone and shale beds. In addition to commonly observed graded bedding, some other textures characteristic for event sedimentation of tempestites and turbidites were recorded — sole markings, particularly load casts enhanced by superimposed layer-parallel compression and cleavage development (Fig. 3G), and convolute bedding in some beds (Fig. 3A). Occasionally, the ball-and-pillow structures were detected as well. Besides these, sporadic soft-sediment slump folds were observed in a quarry near Hrušovo village. These are small-scale bedding contortions confined to certain slump volumes, which are showing no geometric relations to tectonic folds developed in the fully indurated sediments characterized below. Their hinges are moderately to steeply dipping and slightly curved (Fig. 3B), while their axes plot in the NW–SE (ca 145°) direction after back-tilting of bedding into a horizontal position. Their asymmetry indicates a generally south-westward inclined palaeoslope of the sedimentary basin.

First deformation stage

The first observed deformation stage D1 is related to vertical flattening achieved by compaction and pure shear contraction in shales and by a volume loss due to pressure solution especially in marlstones and limestones. This deformation is characterized by discrete S1 foliation which is penetrative in shaly and marly sediments of the Werfen and also of the Dvorníky fms. In the studied cases, it is macroscopically parallel to bedding, hence forming a combined S01 foliation. However, an obliquity of S1 foliation with respect to the sedimentary lamination given by alternation of clay-rich and silty layers was detected in some thin sections (Fig. 4A). Hence, although not directly observed, it might be inferred that the structural paragenesis of the D1 stage also includes small-scale intrafolial folds F1. If so, the D1 structures would indicate not only deep burial, but also the layer-parallel shear likely reflecting crustal thickening due to thrust stacking, which is otherwise obvious from the regional context. This is also corroborated by a very low-grade metamorphic recrystallization, which accompanied development of the S01 foliation. The estimated burial depths reached some 10–15 km (see below).

In the Triassic carbonates, the S01 foliation is less distinctive, forming anastomosing arrays of solution seams in marly limestones of the Reifling and Pötschen fms. Dolomites and massive limestones often lack traces of this foliation, whilst in pure, coarse-grained marbles of the Steinalm (Honce) Fm. it is sometimes outlined by indistinct schistosity and oriented smears of ferruginous pigment.

Second deformation stage

The second deformation stage D2 resulted from the general NW–SE to N–S compression with a common development of F2 folds and their axial-plane S2 cleavage. In the studied area, the D2 stage is dominantly represented by meso-scale folds with SW–NE oriented axes (Fig. 5D). It can be stated from the measured dips of fold limbs and axial planes that the metre-scale folds are mostly symmetrical, and only locally slightly asymmetrical. Their axial planes are mostly steeply SE-dipping up to vertical (Figs. 3D and F, 5E), but the north-west dips are common as well (Fig. 3C and E). The associated axial-plane cleavage is subvertical and generally WSW–ENE trending, parallel to the regional strike of the bedding (Fig. 5A and C). The S2 foliation is represented by the zonal crenulation cleavage formed by pressure solution in marlstones of the Szin Member (Figs. 4B, 3E and F), or by the discrete spaced cleavage in shales and siltstones of the Bôdvaszilas Member (Fig. 3G).

Asymmetrical folds with the SE-dipping S2 cleavage were documented for instance in shales of the Bôdvaszilas Member located 1.5 km south-east of the village of Lípovec (Lípovec 04 site; Fig. 3D) along the forest road cut in the Lipský potok stream valley. Folded Lower Triassic strata of the Turňa Unit are also well exposed in the Drienok Valley to the east of the Lípovec 04 site. Axial planes constructed from measured fold limbs are generally subvertical with the SW–NE strike and small dip fluctuation towards the north-west or south-east (Fig. 5E). In the competent layers (predominantly sandstone), open folds predominate, while folding of the incompetent strata (mainly siltstone and shale) generated close to tight, in places up to isoclinal folds with well-developed S2 cleavage.

Mesoscopic folds with NW-dipping axial planes occur in southern limits of larger outcrop-scale anticlines, where they seem to be passively rotated due to increase of amplitude of the large-scale folds. The locality Zliabok 2 (ZLA 02) occurring in the Veľký Bľh Valley, north of the village of Hrušovo, may serve as an example. The outcrop exposes shales and sandstones of the Bôdvaszilas Member. The lower portion of the outcrop consists thick-bedded sandstones with a well-developed open fold with a steeply NW-dipping axial plane, whereas the upper part of the outcrop is composed of shales with minor folds (Fig. 3C). The dips of cleavage planes, particularly in incompetent shales, vary from steep north-western dip up to subvertical position and thus the
cleavage forms an indistinct fan around the larger-scale fold hinge.

A slightly different folding style was observed in soft marly shales of the Szin Mb., for example, in the limbs of the Sása synform. The metric, close to tight folds are accompanied by cm-scale Z-, S- and M-type secondary parasitic folds in their limbs and hinges (Fig. 3E and F). The Szin marlstones are the least competent rocks of the Turňa Unit, which accounts for development of the most compressed structures with penetrative S₂ crenulation cleavage preferably in these sediments (Fig. 4B).

**Third deformation stage**

In addition to the WSW–ENE oriented S₂ cleavage, which was activated during

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**Fig. 4.** A — photomicrograph of laminated shales and siltstones of the Bódvaszilas Member documenting development of the S₁ foliation (horizontal solution seams) obliquely to bedding. Scale bar is in the lower left corner. B — crenulation cleavage S₂ in marlstones of the Szin Member.

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**Fig. 5.** A — rose diagram of the bedding planes; B — contour diagram of poles to bedding; C — rose diagram of two cleavage systems — S₂ in black and S₁ in grey; D — measured and constructed fold axes of the area: black points indicate F₂ and grey points F₁ axes; E — fold axial planes calculated from the fold limbs.
the NW–SE to N–S compression, the NW–SE to N–S orient-
ed, non-penetrative S₁ planar structures were also observed
(Fig. 5C). The S₁ planes are widely spaced and developed
under the compressional tectonic regime with the generally
WSW–ENE orientation of the maximum shortening axis
parallel to the axial planes of angular and kink-type folds,
which were observed predominantly in shales and mar-
stones of the Werfen Fm. (Fig. 3H). In more competent rocks
like thick-bedded to massive sandstones, the S₃ foliation is
nearly missing. Apart from the measured F₃ fold axes, axial
undulation of F₂ folds is documented by the girdle of F₂ axes
(Fig. 5D). They indicate a later modification of F₂ folds by
the WSW–ENE compression, as well.

Interpretation and discussion

Map-scale structures of the Slovenská skala partial nappe

In the studied area, the Turňa Unit overthrusts slices of the
Meliotic Bôrka Nappe and the Generic Lower Paleozoic
basement and Upper Paleozoic cover rocks to the north, and
is overridden by the Silica Nappe in the south (Figs. 1 and
2). However, the tectonic affiliation of some occurrences of
Meliotic rocks, as shown in Fig. 1, was reinterpreted by
Lačný et al. (2015). Based on lithology and structural rela-
tionships they are now considered to be the frontal elements
of the Turňa Unit.

In the present paper, we also reinterpret the position of the
Meliotic tectonic inlier (window) near the village of
Striežovce (cf. Gaál 1982) in the western part of the investi-
gated region (Figs. 1 and 2). Our view is based on the general
structure of this occurrence of Middle–Upper Triassic forma-
tions that are surrounded by the upper Lower Triassic Szín
marlstones, thus indicating a synclinal structure. Moreover,
the Triassic carbonates in the synclinal core do not exhibit
the typical “Meliotic” structure with olistoliths embedded in
Jurassic shales, but fragments of continuous successions can
be documented. Consequently, the sequence of metamor-
phosed Triassic carbonates located in this syncline is now re-
garded as a component of the Turňa Unit. The presence of
red marly and siliceous shales of probably Ladinian age
(work in progress) near the village of Hrušovo is a particu-
larity of the Striežovce succession, indicating its more distal
passive margin position with respect to other Turňa succes-
sions.

The map-scale structures of the Turňa Unit (Slovenská
skala partial nappe) have a slightly arcuate shape changing
from SW–NE strike in the western up to W–E strike in the
eastern part of the area (Fig. 2). This trend is well expressed
by axes of several subparallel anticlinal and synclinal zones,
which were thoroughly described and named already by
Gaál & Mello (1983). Macroscopic synclines are filled by
upper Lower Triassic Szín marlstones and the widest ones
also by Middle–Upper Triassic carbonates and shales (Tri-
peniažky–Slovenská skala, Sása and Striežovce synclines,
Fig. 2). These map-scale synclines are clearly asymmetrical
with steeply south-dipping axial planes, as seen in cross-
sections constructed from the bedding attitudes. The northern
limbs of synclines along the northern edge of the Turňa Unit,
at the contact with the underlying Gemer Unit (Tri peniažky–
Slovenská skala; Fig. 2), are truncated by moderately south-
dipping reverse faults linked to the basal overthrust plane in
places (e.g., the Rákoš area — cf. Lačný et al. 2015; Fig. 2),
or imbricated with the underlying Meliatic complexes
(northern slopes of the Tri peniažky Hill). In a map view
(Fig. 2), the macroscopic synclines appear to be non-cylin-
drical, with doubly-plunging hinges (e.g., the Sása and
Striežovce brachysynclines). This might be a cumulative ef-
fact of a sinistral transpression especially in the western part
of the area with SW–NE structural trends (see Lexa et al.
2003), and the superimposed W–E shortening with large-
scale, gentle folds with roughly N–S oriented axes revealed
by the mesoscopic structural analysis (see below).

In the northern and central parts of the investigated area,
the synclines alternate with somewhat wider open anticlines
composed of the Bôdvaszilas shales and sandstones. How-
ever, the southern anticlinal zone at the contact with the
overriding Silica Unit is more complicated. The dominant
structure is the large Brusník anticline cored by the Upper
Palaeozoic rocks of the Turiec and Brusník fms (Fig. 2). The
axis of this anticline plunges rapidly to the NE; hence this
structure can be classified as a brachyanticline or pericline.
Close to the east, the Brusník pericline is juxtaposed by
another antiform, which is the Držkovce tectonic window
exposing the Meliatic complexes, which likely underlay the
whole Turňa Unit in this area, as was revealed by the BRU-1
borehole. This borehole, drilled in the core of the Brusník
anticline, encountered Jurassic olistostromatic complexes of
the Meliata Unit directly below Carboniferous rocks of the
Turiec Fm. (Vozárův & Vozár 1992).

Another borehole DRZ-1 drilled directly in the Držkovce
tectonic window penetrated several alternating slices of Me-
liotic and Turnaic rocks (Mello et al. 1994). The latter are
mostly composed of Lower Triassic shales and presumably
Upper Permian coarse-grained clastics (Brusník Fm.), as
well as shales and evaporites with blocks of serpentinites and
various carbonates. The evaporitic mélangé with blocks of
ultramafic magmatites resemble the Perkupa Fm. of northern
Hungary (e.g., Réti 1985), or the Haselgebirge salt breccias
of the Northern Calcareous Alps (Kirchner 1980; Schorn et
al. 2013). If present in a sedimentary succession, the extre-
mely incompetent evaporites serve as décollement hori-
zons and are often found at the soles of far-travelling cover
nappes, where they often incorporate various footwall-de-
ived exotic fragments.

Based on its internal structure, the Držkovce tectonic win-
dow may be interpreted as a large-scale, imbricated duplex
structure (Fig. 2, cross-section A), which was formed in front
of the buttressing Brusník antiform. Accordingly, it most
probably originated after the main overthrusting phase of the
Turňa Unit and can be classified as an out-of-sequence thrust
structure of the D₂ stage.

The two anticlinal macrostructures — the Brusník peri-
cline and the Držkovce imbricated antiform — are laterally
substituted in a coulisse-like way, the Brusník pericline
being a more southern one (Fig. 2, sections A and B). This
suggests that the Brusník body is somewhat structurally

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independent internal part of the Turňa Unit formed by additional post-thrusting shortening, large-scale folding and thrusting with development of a steep imbricated structure in its front (Fig. 6). Moreover, the basal detachment reached deeper structural levels within the Palaeozoic rocks here, whilst further north it is stepping up into the main evaporitic décollement horizon and then into Triassic sediments. As a result, the overall geometry of fold-and-thrust structures of the Turňa Unit points to its northward thrusting direction in the investigated area.

In general, the bedding planes dip towards the SE and NW throughout the study area with the average inclination between 60 and 70° (Fig. 5A, B). Locally, the bedding is sub-vertical. Rocks are also affected by superimposed, in places penetrative cleavage related to mesoscopic folding. Cleavage is steeply NW- or SE-dipping dependent on position within large-scale fold structures, as will be described below.

The studied region is also affected by a set of transversal, generally NW—SE striking, map-scale faults. A majority of them are related to the post-thrusting, most likely Miocene tectonic activity. However, short local faults that cut carbonate complexes in synclinal cores can be interpreted as tear faults that were active simultaneously with growth of the synclines.

**Origin and evolution of the Meliata-Turňa accretionary wedge**

The largest part of the studied area is composed of incompetent shales of the Werfen Fm., which are characterized by the penetrative, bedding-parallel S01 foliation produced by vertical flattening of originally gently dipping strata. Relying on the supposed palaeogeographical position of the Turňa Unit on the flanks of the Meliata Ocean, its origin was most probably caused by a tectonic burial related to formation of the accretionary wedge during subduction processes and closure of the Meliata Ocean in the Late Jurassic to earliest Cretaceous times (e.g., Faryad 1995, 1999; Mello et al. 1998; Mock et al. 1998; Őrkai et al. 2003; Dallmeyer et al. 2008). As a result, all rocks of the Turňa Unit were buried within the nappe pile of the accretionary wedge and were affected by a very low-grade metamorphism.

However, the conditions of metamorphism seem to vary from place to place and no direct petrologic determinations of the pressure-temperature conditions of the Turňa Unit rocks are available yet from the investigated area. Referring to data obtained from Mellatic rocks of the Držkovce and Meliata tectonic windows (see Fig. 2), and from the possibly Turňa Unit metasediments near Hačava village further to the

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**Fig. 6.** Scheme of development of large-scale fold and thrust structures of the Turňa Nappe in the examined area. A — deformation stage D1 during the thrust stacking period and growth of the accretionary wedge. B — situation after the D2 stage characterized by out-of-sequence thrusting. Not to scale.
east, the maximum $P$-$T$ conditions may be estimated to 300–350 °C at 300–400 MPa (Árkai et al. 2003). According to K-Ar dating of white K-mica concentrates, the thermal peak of this metamorphic event probably occurred during the earliest Cretaceous, some 145–140 Ma ago (Árkai et al. 2003). Analogous rocks of the Turňa (Torna) Unit in the Rudabánya Mts. of northern Hungary provided similar metamorphic temperatures of approximately 300–350 °C at pressures of 300–450 MPa (Árkai & Kovács 1986; Kővér et al. 2009). This prograde metamorphic event was coeval with partial retrogression of the Meliata HP/LT rocks in the greenschist-facies conditions (e.g., Faryad 1995, 1999; Dallmeyer et al. 2008) and likely reflects the maximum thickening of the wedge due to thrust stacking, including exhumed blueschist Meliata slices at the wedge sole (Fig. 6A).

Subsequent $D_2$ compression and out-of-sequence thrusting within the accretionary prism might have been induced by its frontal collision with the Gemenic margin of the Central Western Carpathian block (Fig. 6B). It resulted in development of the SW–NE striking, in places fanning $S_2$ foliation. In the Bódvaszilas shale-sandstone strata, the related $F_2$ folds are open to closed, partly slightly asymmetrical showing both the north-western and south-eastern inclinations of axial planes. The model of fan-wise arrangement of fold axial planes developed during a single deformation phase is outlined in Fig. 7A. The model is based on numerous examples from structural geology textbooks (e.g., Ramsay & Huber 1987) of polyharmonic folds resulting from a variable lithology, thickness and competence contrast of strata in a deformed multilayer. These fold patterns predominantly occur in the SW–NE trending anticlinal hinge zones and cores of large-scale folds.

In the less competent media, like the Szin marlstones, the minor tight to isoclinal folds were tightened by flexural flow and pressure solution along the $S_2$ cleavage planes. The consequential fold geometry shows typical Z-, M- and S-type “parasitic” folds (conceptual model in Fig. 7B). These folds mostly occur in limbs of large-scale folds.

The deformation record of this second tectonic phase was also observed in the Meliata Nappe close to the village of Držkovce, while mesoscopic structures of this stage were not detected with certainty in adjacent parts of the Silica Nappe. The reason could be either a higher structural position of the Silica Nappe and its decoupling from the underlying deformed units within the wedge, or that it was still not a part of the Neotethyan accretionary wedge during the Late Jurassic and Early Cretaceous. However, the Silica Nappe as a whole is also affected by large-scale, W–E trending fold-thrust structures in the Slovenský kras Mts. (Mello et al. 1997) and also in the adjacent Aggtelek-Rudabánya Mts. in northernmost Hungary (Less et al. 1988; Hips 2001; Kővér et al. 2009; Deák-Kővér 2012). However, relics of Upper Cretaceous, Gosau-type sediments (conglomerates, fresh-water limestones, palaeokarst fillings) incorporated into these structures point to their post-Cretaceous age (Mello et al. 1997).

**Shortening in the ENE–WSW direction**

This tectonic stage is characterized by the orientation of the principal compression axis in the WSW–ENE direction. The $F_3$ fold group is represented by less distinct, open to closed and mostly angular folds and kink bands, in places accompanied by the approximately N–S oriented, widely spaced subvertical planes subparallel to the $F_3$ axial planes (Fig. 5C). Due to a more brittle character of $D_3$ structures compared to $D_1$ and $D_2$, indicating some exhumation between the $D_2$ and $D_3$ stages, the $D_3$ structures are considered to be younger than the $D_2$ structural association. Modification of $D_2$ structures by the $D_3$ phase is also indicated by a girdle of $F_2$ fold axes (Fig. 5D), interpreted as their plunge undulation due to superimposed $F_3$ macroscopic folding.

However, the measured $F_1$ fold axes are poorly presented in tectonograms (Fig. 5D) for several reasons. The first reason is the less significant manifestation of this event in the field. The second important reason can be the morphology of the area, where most of the incised valleys with well-outcropping rocks trend in a NW–SE direction. Consequently, only a few outcrops that would trend perpendicularly to $D_3$ structures are present.

Nevertheless, structures of this deformation stage were also observed in the Meliata and Silica units. For example, a set of kink folds was studied in Lower Triassic strata of the Silica Unit near Krásnohorská Dlhá Lúka village south of the town of Rožňava. Their 5 measured axes plunge moderately (30–60°) towards the SE (105–170°). The folds of this direction were also described from the Hungarian territory.
parallel S1 low-grade metamorphic foliation. Subsequently, and the development of the D2 fold-and-thrust structures that with the southern Gemeric margin led to its overthrusting the Early Cretaceous collision of the accretionary wedge (for instance the Držkovce window and Brusník borehole), or more commonly it seems to form synclines, originally Jurassic sedimentary basins, in the Turňa and/or Silica units (like the Meliata type locality — Aubrecht et al. 2012). The relationship of ophiolite-free and ophiolite-bearing olistostromes/mélanges is not clear, possibly the former underlie the latter, as it was documented in the Darnó Mts. of northern Hungary (Kovács 1988; Dimitrijević et al. 2003; Kovács et al. 2010).

The first phases of development of the Meliata accretionary complex composed of detached Jurassic sediments and various mélange/olistostrome complexes are indirectly dated by commencement of synorogenic clastic sedimentation during the late Early—Middle Jurassic. The rock composition of the wedge was complete during the latest Jurassic by incorporation of the exhumed blueschist complexes and termination of synorogenic sedimentation before the Kimmeridgian. Sediments younger than Oxfordian are virtually absent in the whole Meliata-Turňa-Silica nappe stack, except for shallow-water Kimmeridgian—Tithonian limestones found as pebbles in Senonian and Oligocene conglomerates (Mišík & Sýkora 1980). These indicate that the accretionary wedge was partially sealed by a shallow carbonate platform which was completely eroded later (Plassen platform of uncertain position in Fig. 8). Subsequently, ca 150—140 Ma ago, various Meliata-Turňa rock complexes were buried to depths of some 10—15 km in lower parts of the wedge and underwent a prograde metamorphic recrystallization (Árkai et al. 2003), while the older blueschists of the Bôrka Nappe were partly retrogressed (e.g., Faryad 1999; Dallmeyer et al. 2008). The early phase of blueschists exhumation occurred ca 147 Ma, as indicated by the electron microprobe dating of retrogression-related monazite (Méres et al. 2013). These processes are only feebly registered by the structural record of the first deformation stage D1, however.

Later on, both the Turňa and Meliata units collided with and were thrust over the underlying Gemericum as a united structural complex (Fig. 6). The thrusting event ca 140—130 Ma (Vozárová et al. 2008) was followed by the subsequent stage of exhumation, collapse and cooling of the wedge some 130—120 Ma ago, as documented by (U-Th)/He zircon thermochronology from the Meliatic rocks (Putiš et al. 2014). Simultaneously, detritus of the HP minerals appeared for the first time in sediments of this age — in the Barremian—Aptian, Urgon-type platform limestones occurring as pebbles in the Albán–Cenomanian conglomerates of the Klape Unit (Méres et al. 2015; cf. Fig. 8). After this thrusting event the Meliata-Turňa stack became a component of the southern Central Western Carpathian orogenic wedge, including the underlying Gemer and Vepor basement-cover thrust sheets,
which propagated northwards during the Albian–Turonian (110–90 Ma). By this time, erosional products of Meliatic rocks became commonly present in “exotic” conglomerates of the Pieniny Klippen Belt and adjacent zones (Fig. 8; see e.g., Plašienka & Soták 2015 for the latest summary). The ensuing thickening of the orogenic wedge rear and its subsequent extensional collapse and cooling are well constrained by the Late Cretaceous thermochronological data in the time span ca 90–55 Ma (e.g., Janák et al. 2001; Koroknai et al. 2001; Plašienka et al. 2007; Hurai et al. 2008; Králiková 2013; Méres et al. 2013, 2015; Vojtko et al. 2016; for the reviews see also Putiš et al. 2009 and Jeřábek et al. 2012). In the southern Central Western Carpathian zones (Vepor-Gemer Belt), material of the Meliatic ophiolites occurs massively in the uppermost Cretaceous—lowermost Palaeocene, Gosau-type conglomerates (e.g., Hovorka et al. 1990) – cf. Fig. 8.

Nevertheless, the yet unresolved question remains: How is the Silica Nappe related to the structures of the underlying Meliatic-Turnaic units? The conventional concept considers the Silica Nappe in the Slovak-Agtelek Karst Mts. and its analogues further north (Stratená, Vernár, Muráň and Drienok nappes — “Silicicum” s.l.) as the non-metamorphosed cover nappe system, which in the highest structural position within...
the Palaeoalpine thrust stack of the Central Western Carpathians. The Silicic nappes are overlying various units (Generic, Veporic, Hronic — Fig 8) with a distinct metamorphic and structural discordance (e.g., Kozur & Mock 1973, 1987, 1997; Mello et al. 1997; Plašienka et al. 1997). On the contrary, some other data indicate that the Silicicum is composed of several partial units that are of heterogeneous origin from the lithostratigraphic-facies and structural-metamorphic points of view (e.g., Havrila & Ožvoldová 1996; Vojíkovo 2000; Gawlick et al. 2002; Havrilov 2011). Consequently, the present concept of the Silicicum as a unified superunit might be misleading and its various subunits could be of different palaeogeographic provenances, structural-metamorphic histories and times of final emplacement. It is not to be excluded that the Silica Nappe is not a coherent body, but its slightly metamorphosed subunits were possibly components of the early accretionary wedge, whilst the flat-lying carbonate slabs may have glided to their present position later, during the late Cretaceous-earliest Palaeogene gravitational collapse of rear parts of the orogenic wedge.

In comparison with the Northern Calcareous Alps (NCA), the Triassic lithostratigraphic succession of the Turňa Unit roughly corresponds to the Hallstatt Zone, occurring as a re-worked material in the Hallstatt Mélange of the Jurassic Lammer Basin (Upper Tirolic nappe system — e.g., Missoni & Gawlick 2011a, b; Gawlick et al. 2012). Unlike the Alpine reworked olistostromal complexes in secondary position, the Turňa and Silica units mostly show continuous sedimentary successions in primary nappe positions, albeit redistributed by a subsequent out-of-sequence imbrication within the accretionary wedge. On the contrary, with a few exceptions (Šýkora & Ožvoldová 1996), Middle-early Late Jurassic deep-water basins with mass-wasting deposits are nearly missing in the southern Carpathian zones. This makes correlation difficult, even though the Triassic facies zones can be followed and mutually related relatively easily. What appears to be really different is the tectonic structure of the nappe edifice in both mountain ranges.

The southern Western Carpathian zones are regarded as the north-eastern prolongation of the Jurassic Neotethyan Orogenic Belt extending from the Dinarides, Albanides and Hellenides NW-ward to the NCA (Gawlick et al. 2012 and references therein). These southern parts of the Neotethyan Belt are characterized by extensive ophiolite obduction in the late Middle-early Late Jurassic sealed by the Upper Jurassic-earliest Cretaceous carbonate platforms (e.g., Schmid et al. 2008). An analogous situation is inferred for the NCA, notwithstanding that ophiolite complexes were completely eroded during the Cretaceous and early Palaeogene (cf. Kriscie et al. 2014; Gawlick et al. 2015). In all these zones from the Hellenides up to the NCA, the obducted ophiolite nappes occur in the uppermost structural position above an imbricated thrust stack of the former Neotethyan passive continental margin and shelf areas. However, the structural situation is very much different in the inner Western Carpathian zones. As described above, the Jurassic ophiolite-bearing mélange and/or blueschist nappe (Melitiumic s.l.) overlies directly and primarily the Geric basement/cover complexes, namely the Central Austroalpine unit in Alpine terms. However, the Meliatic complexes are overridden by the passive margin thrust stack in an “improper” sequence, namely first by the Triassic distal margin to upper slope succession (Turňa Unit) and then by the outer shelf successions (Silica Unit). Accordingly, the nappe sequence is precisely the opposite of what we would expect. There are numerous models attempting to explain this tectonic vs. palaeogeographic ambiguity (e.g., Kozur 1991; Hók et al. 1995; Kozur & Mock 1997; Less 2000; Lexa et al. 2003; Cántos & Vörös 2004; Hallmeyer et al. 2008; Schmid et al. 2008; Kovér et al. 2009; Kóvér & Fodor 2014), but none of them accounts for all the structural and facies relationships satisfactorily.

The present paper has no ambition to develop a new evolutionary tectonic model of the area; neither has it directly followed any of the previously formulated concepts. In our opinion, there are still too many fundamental uncertainties that hamper development of a reliable hypothesis that would agree with the majority of existing structural, metamorphic and lithofacies data. For the time being, we see relationships of the Meliata-Turňa thrust stack with the overlying complexes that are presently affiliated with the Silicicum as the major open question of the structure and evolution of the southern Western Carpathian zones. This problem should be one of the main targets for future research in the area concerned.

Conclusions

Structural analysis of fold and cleavage deformation structures of the western part of the Turňa Unit revealed their successive development in three deformation stages. It is inferred that the first deformation stage D1 was related to initial stages of an accretionary wedge development formed in response of the Neotethyan (Meliata) Ocean subduction during the Late Jurassic. Thrust stacking brought about very low-grade metamorphism in lower parts of the wedge, accompanied by vertical flattening and development of the penetrative, bedding-parallel foliation S0. At the same time, the wedge incorporated Meliatic ophiolite fragments and various mélangé complexes, as well as the exhumed HP/LT metamorphic slabs derived from the subducted distal passive continental margin (Bőrka Nappe). These events took place in the Late Jurassic.

Suturing of the Meliata Ocean and collision of the Meliata-Turňa accretionary wedge with the southern passive European margin, represented by the Gemer Unit, is recorded by the second deformation stage D2. It is expressed particularly by folding on all scales, whereby the macroscopic asymmetric folds with a generally northern vergence dominate the structure of the area by a system of SW-NE to W-E trending synclines filled with Middle-Upper Triassic carbonates and anticlines formed by Lower Triassic clastic sediments. The southernmost Brusník brachyanticline also involves Upper Palaeozoic sedimentary complexes in its core. Its frontal zone is complicated by the presence of an antiformal imbricated duplex which exposes rocks affiliated with the Meliata Unit (Držkovce tectonic window).
The geometry of the mesoscopic $F_2$ folds depends on the rheology of folded media. In shale-sandstone multilayers, folds are open to closed, upright to steeply inclined and form polyharmonic sets. Marly shales are characterized by minute tight to isoclinal folds with penetrative axial-plane cleavage and can often be regarded as parasitic folding occurring in limbs of larger-scale upright folds. Regional considerations point to timing of the $D_2$ stage during the Early Cretaceous period. Deformation was followed by exhumation and erosion of the former Meliata-related accretionary wedge within the rear parts of the prograding Central Western Carpathian collisional orogenic system. Timing of emplacement of the overlying Silica Nappe is not clear. Whereas the $D_2$ structural pattern points to the NW—SE to N—S shortening, the third deformation stage likely occurred during the latest Cretaceous to early Palaeogene and also affected rocks of the Silica Nappe. During the Oligocene and Early Miocene, the area was covered by a shallow epicontinental sea. Erosional remnants of its sediments, along with Middle Miocene volcanic complexes, still cover considerable parts of the southern Carpathian zones and largely obliterate the relationships of Mesozoic tectonic units in this complex suture zone of the Carpathians.

Acknowledgements: This work was financially supported by the Slovak Research and Development Agency under the contract Nos. APVV-0315-12 and APVV-0212-12. It is also an outcome of the research project VEGA 1/0193/13. Financial support from the respective grant agencies is gratefully acknowledged. Constructive review comments by L. Fodor (Budapest) and J. Hók (Bratislava) that helped to improve the scientific content and clarity of the text and figures are gratefully acknowledged.

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