GEOLOGICA CARPATHICA, APRIL 2016, 67, 2, 177–193 doi: 10.1515/geoca-2016-0012

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-Rhenodanubian-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 Cretaceous to Miocene. 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 Tatric, Veporic and Gemeric from bottom to top) and three large-scale cover nappe systems (Fatric, 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; Mello et al. 1997; 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 Rudabánya 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 ambiguously 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 Rudabánya 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 Turnaicum 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 Gemeric Mesozoic" cover of the Gemeric basement (e.g., Bystrický 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 nappes (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 Rudabánya Mts. overthrusts the Silicic Bódva 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).

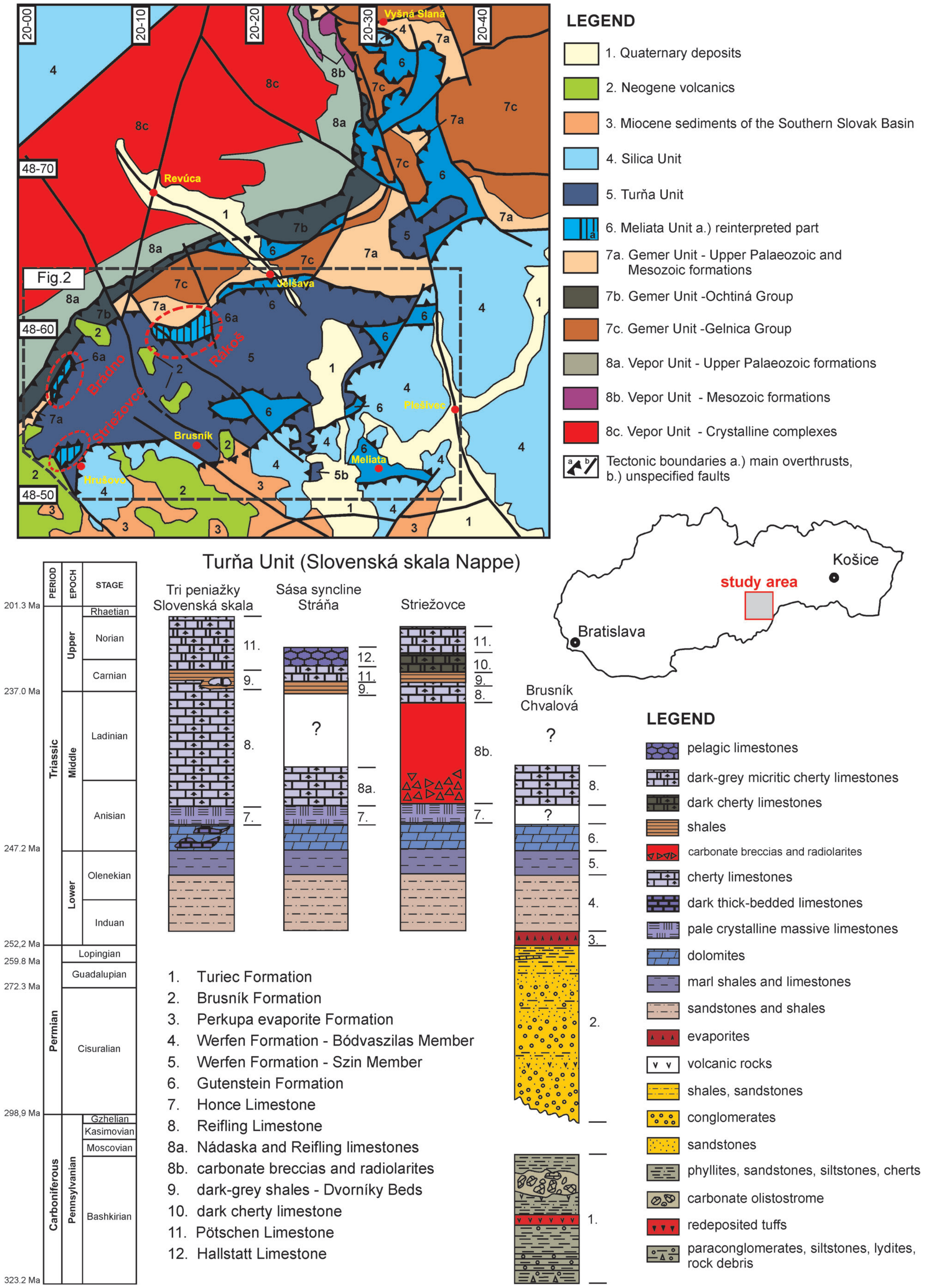
In order to decrease the number of local names with various meanings to a minimum, we shall treat the terms Turňa (Turnaicum), Torna (Tornaicum) and its various partial nappes as synonyms of the reduced term Turňa Unit, which will be used throughout the following text.

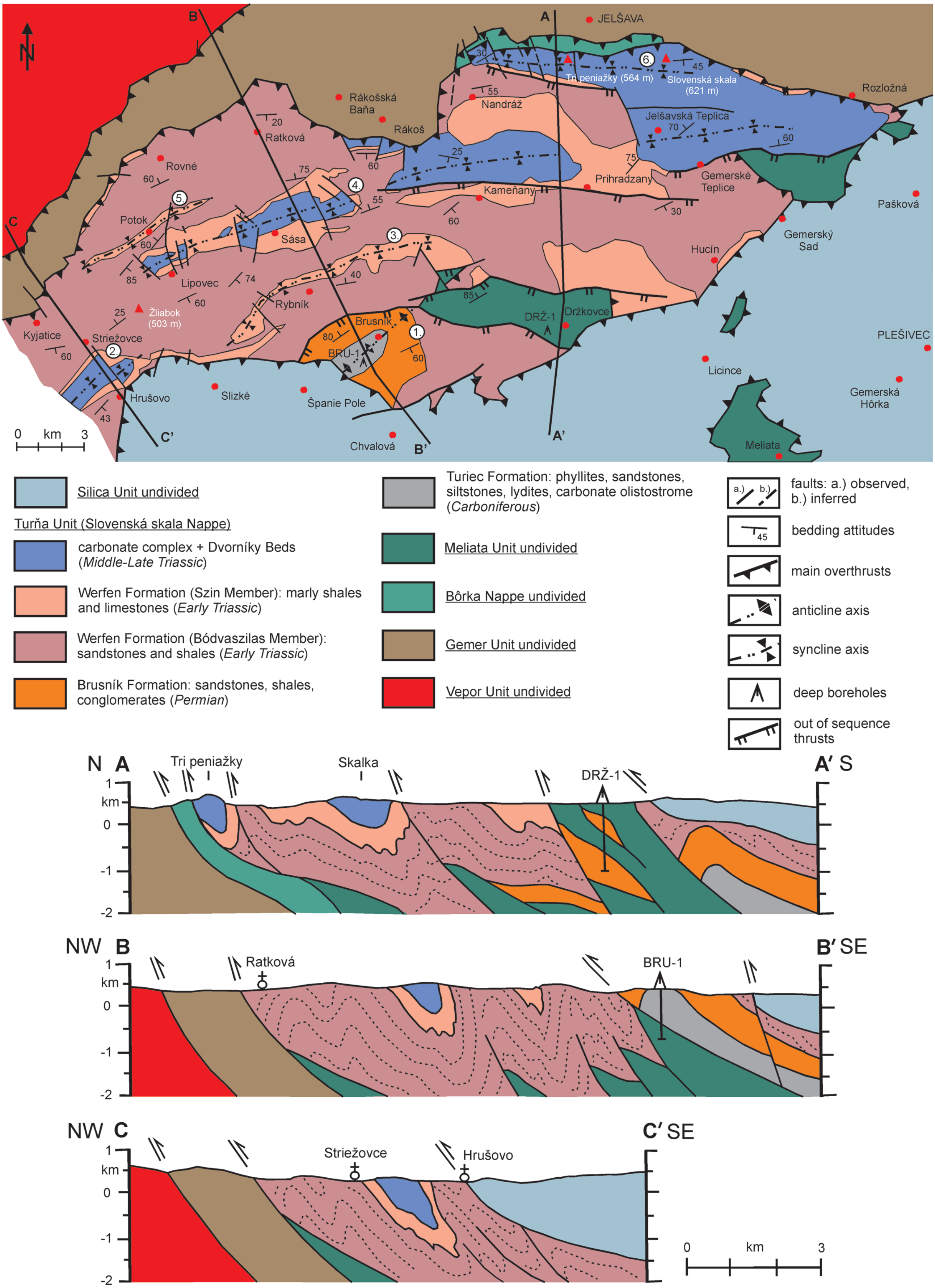
Treated in this way, the Turňa Unit outcrops predominantly in the southern part of the Slovenské rudohorie, Revúcka vrchovina and Slovenský kras Mts. in south-eastern Slovakia and also in the Rudabánya Mts. in north-eastern Hungary. The south-eastern boundary of surface occurrences of the Turňa Unit 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 Bódvaszilas Member (originally defined as a formation by Hips 1996) composed of variegated sandstones and shales over-

Fig. 1. Geological sketch map of the study area (framed region, see Fig. 2) and its surroundings and lithostratigraphic columns of several sections of the Turňa Unit (simplified and supplemented according to Mello et al. 2008). Oval dashed lines mark the reinterpreted areas — Brádno and Rákoš by Lačný et al. (2015), and Striežovce in this work.


20-00
20-10
20-20
20-30
20-40
48-70
48-60
48-50
Fig.2
Vyšná Slaná
Revúca
Jelšava
Plešivec
Brusník
Meliata
Hrušovo
Brádno
Rákoš
Striežovce
LEGEND
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. Gemer Unit - Upper Palaeozoic and Mesozoic formations
7b. Gemer Unit -Ochtiná Group
7c. Gemer 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
Košice
study area
Bratislava
Turňa Unit (Slovenská skala Nappe)
Tri peniažky Slovenská skala
Sása syncline Stráňa
Striežovce
Brusník Chvalová
PERIOD
EPOCH
STAGE
201.3 Ma
237.0 Ma
247.2 Ma
252,2 Ma
259.8 Ma
272.3 Ma
298,9 Ma
323.2 Ma
Triassic
Upper
Middle
Lower
Rhaetian
Norian
Carnian
Ladinian
Anisian
Olenekian
Induan
Permian
Lopingian
Guadalupian
Cisuralian
Carboniferous
Pennsylvanian
Gzhelian
Kasimovian
Moscovian
Bashkirian
1. Turiec Formation
2. Brusník Formation
3. Perkupa evaporite Formation
4. Werfen Formation - Bódvaszilas Member
5. Werfen Formation - Szin Member
6. Gutenstein Formation
7. Honce Limestone
8. Reifling Limestone
8a. Nádaska and Reifling limestones
8b. carbonate breccias and radiolarites
9. dark-grey shales - Dvorníky Beds
10. dark cherty limestone
11. Pötschen Limestone
12. Hallstatt Limestone
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 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


N
B
A
JELŠAVA
C
Rákošská Baňa
Rákoš
Ratková
Rovné
Nandráž
Tri peniažky (564 m)
Slovenská skala (621 m)
Rozložná
Jelšavská Teplica
Prihradzany
Gemerské Teplice
Kameňany
Potok
Sása
Lipovec
Rybník
Žliabok (503 m)
Kyjatice
Striežovce
Hrušovo
Slizké
Španie Pole
Brusník
BRU-1
DRŽ-1
Držkovce
Hucín
Gemerský Sad
Pašková
PLEŠIVEC
Licince
Gemerská Hôrka
Meliata
Chvalová
C'
B'
A'
0 km 3
Silica Unit undivided
Turňa Unit (Slovenská skala Nappe)
carbonate complex + Dvorníky Beds (Middle-Late Triassic)
Werfen Formation (Szin Member): marly shales and limestones (Early Triassic)
Werfen Formation (Bódvaszilas Member): sandstones and shales (Early Triassic)
Brusník Formation: sandstones, shales, conglomerates (Permian)
Turiec Formation: phyllites, sandstones, siltstones, lydites, carbonate olistostrome (Carboniferous)
Meliata Unit undivided
Bôrka Nappe undivided
Gemer Unit undivided
Vepor Unit undivided
faults: a.) observed, b.) inferred
bedding attitudes
main overthrusts
anticline axis
syncline axis
deep boreholes
out of sequence thrusts
N A
Tri peniažky
Skalka
DRŽ-1
A' S
1 km 0 -1 -2
NW B
Ratková
BRU-1
B' SE
NW C
Striežovce
Hrušovo
C' SE
0 km 3

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 ramp-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 by most probably Carnian, Reingraben-type dark shales (Dvorníky and Tornaszentandrás 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, Rákoš, Nandráž, Ratková, Kameňany, Držkovce, Sása and Jelšava (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 Bódvaszilas 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 S_1 foliation, which is subparallel to the primary S_0 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 Bódvaszilas 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 beds, 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 D_1 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 S_1 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 S_{01} foliation. However, an obliquity of S_1 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 D_1 stage also includes small-scale intrafolial folds F_1. If so, the D_1 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 S_{01} foliation. The estimated burial depths reached some 10–15 km (see below).

In the Triassic carbonates, the S_{01} foliation is less distinctive, forming anastomozing 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.

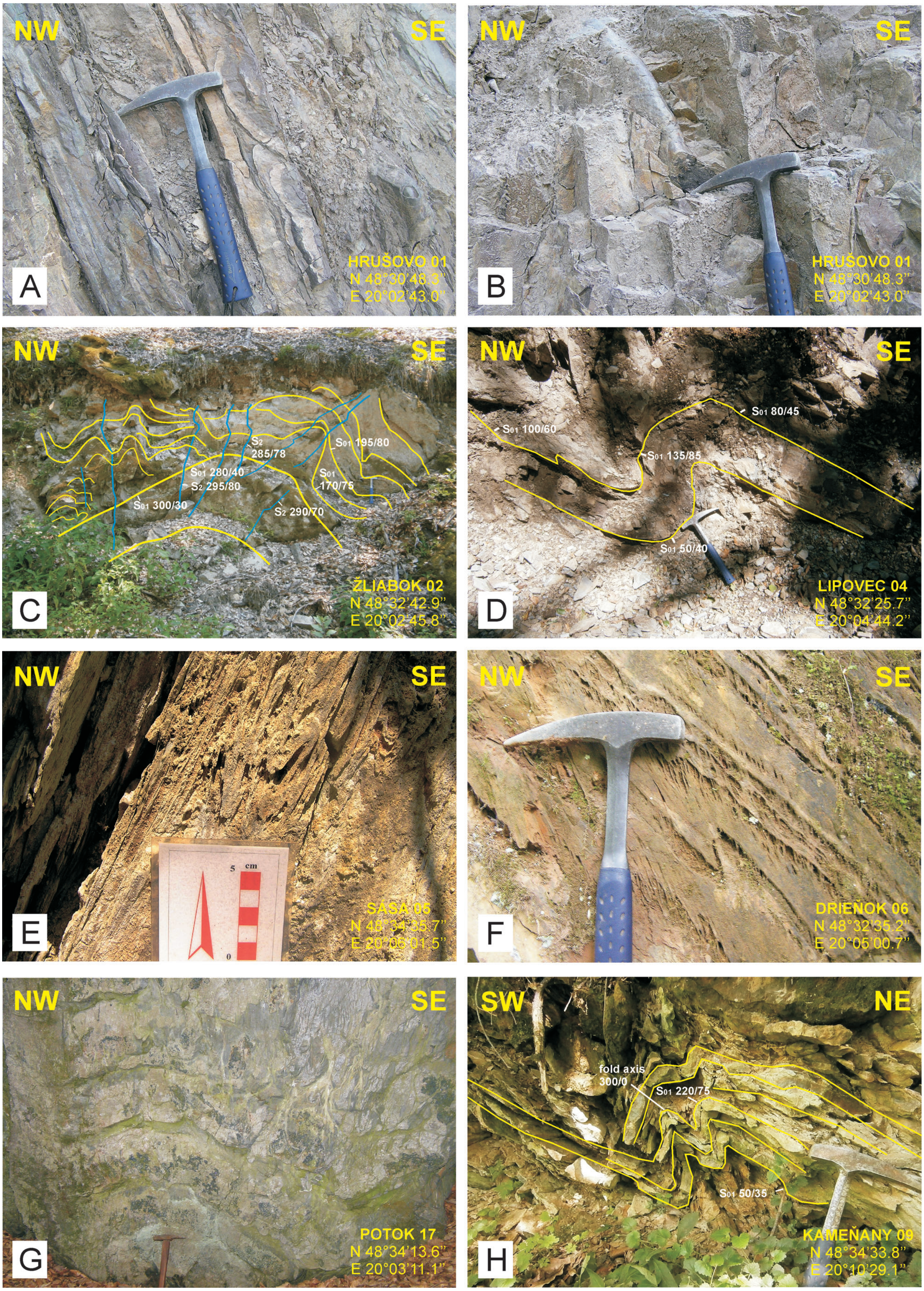
Second deformation stage

The second deformation stage D_2 resulted from the general NW–SE to N–S compression with a common development of F_2 folds and their axial-plane S_2 cleavage. In the studied area, the D_2 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 northwest 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 S_2 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 Bódvaszilas Member (Fig. 3G).

Asymmetrical folds with the SE-dipping S_2 cleavage were documented for instance in shales of the Bódvaszilas Member located 1.5 km south-east of the village of Lipovec (Lipovec 04 site; Fig. 3D) along the forest road cut in the Lipovský potok stream valley. Folded Lower Triassic strata of the Turňa Unit are also well exposed in the Drienok Valley to the east of the Lipovec 04 site. Axial planes constructed from measured fold limbs are generally subvertical with the SW–NE strike and small dip fluctuation towards the northwest 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 S_2 cleavage.

Mesoscopic folds with NW-dipping axial planes occur in southern limbs of larger outcrop-scale anticlines, where they seem to be passively rotated due to increase of amplitude of the large-scale folds. The locality Žliabok 2 (ŽLA 02) occurring in the Veľký Blh Valley, north of the village of Hrušovo, may serve as an example. The outcrop exposes shales and sandstones of the Bódvaszilas Member. The lower portion of the outcrop contains 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

Fig. 3. A — convolute bedding in the Bódvaszilas shale-sandstone sequence, small quarry near village of Hrušovo. **B** — slump fold with steeply plunging axis, the same locality. **C** — outcrop Žliabok 02 in the Blh valley showing dependence of F_2 fold dimensions on the competency contrast between the thick bedded sandstones at the bottom and shales in the upper part of the outcrop. Yellow lines trace the bedding, blue lines indicate the S_2 cleavage planes. **D** — outcrop at the Lipovec locality with asymmetric, NW-verging fold F_2. **E** — Z-shaped folds, Szin marly shales, incision cut of the Turiec River north of Sása village. **F** — S-shaped folds at the Drieňok outcrop, forest road cut about 1 km NW of the Drieňok gamekeeper's lodge. **G** — load casts and ball-and-pillow structures in the sandstone-rich Bódvaszilas Member modified by subvertical cleavage S_2, rock cliff above the road 500 m NW of settlement Potok. **H** — outcrop near Kameňany village documenting minute F_3 fold structure.


NW
SE
A
HRUŠOVO 01
N 48°30'48.3''
E 20°02'43.0''
NW
SE
B
HRUŠOVO 01
N 48°30'48.3''
E 20°02'43.0''
NW
SE
S01 195/80
S2
285/78
S01 280/40
S2 295/80
S01
170/75
S01 300/30
S2 290/70
C
ŽLIABOK 02
N 48°32'42.9''
E 20°02'45.8''
NW
SE
S01 100/60
S01 80/45
S01 135/85
S01 50/40
D
LIPOVEC 04
N 48°32'25.7''
E 20°04'44.2''
NW
SE
5
cm
0
E
SÁSA 05
N 48°34'35.7''
E 20°06'01.5''
NW
SE
F
DRIEŇOK 06
N 48°32'35.2''
E 20°05'00.7''
NW
SE
G
POTOK 17
N 48°34'13.6''
E 20°03'11.1''
SW
NE
fold axis
300/0
S01 220/75
S01 50/35
H
KAMEŇANY 09
N 48°34'33.8''
E 20°10'29.1''

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 S_2 crenulation cleavage preferably in these sediments (Fig. 4B).

Third deformation stage

In addition to the WSW–ENE oriented S_2 cleavage, which was activated during

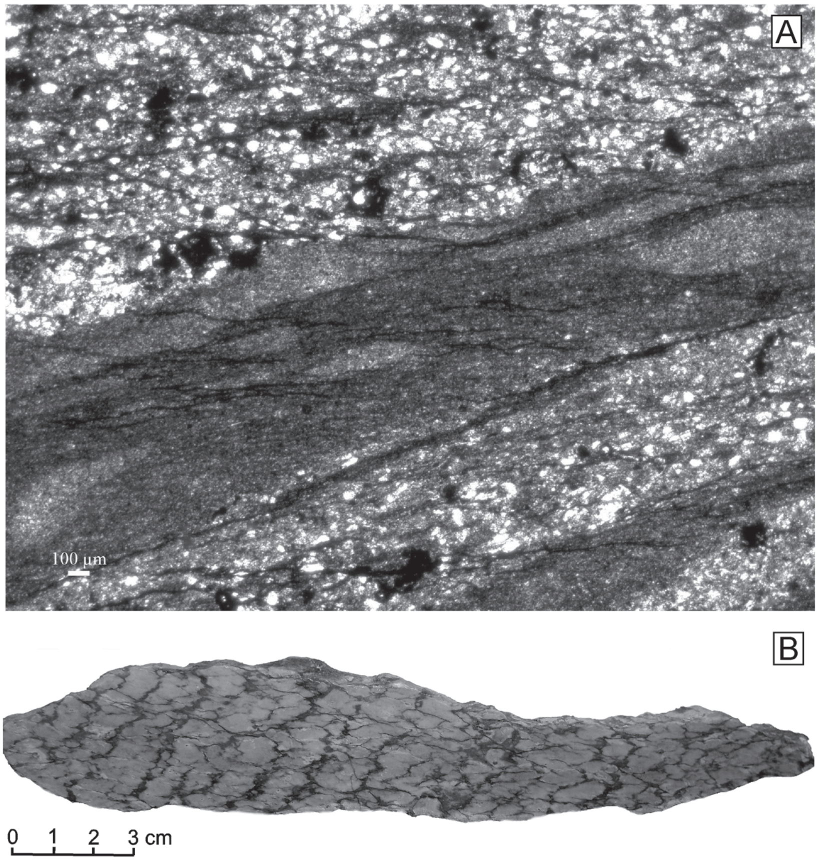


Fig. 4. A — photomicrograph of laminated shales and siltstones of the Bódvaszilas Member documenting development of the S_1 foliation (horizontal solution seams) obliquely to bedding. Scale bar is in the lower left corner. **B** — crenulation cleavage S_2 in marlstones of the Szin Member.

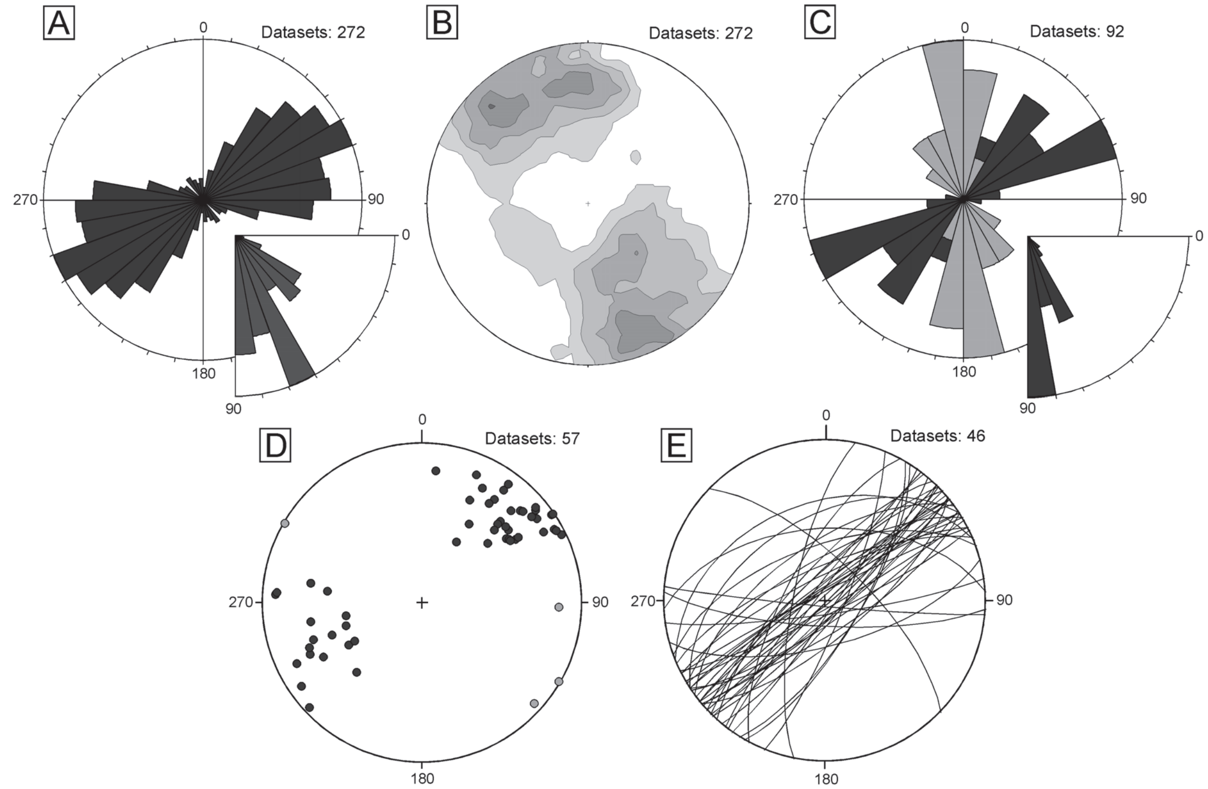


Fig. 5. A — rose diagram of the bedding planes; **B** — contour diagram of poles to bedding; **C** — rose diagram of two cleavage systems — S_2 in black and S_3 in grey; **D** — measured and constructed fold axes of the area: black points indicate F_2 and grey points F_3 axes; **E** — fold axial planes calculated from the fold limbs.

the NW–SE to N–S compression, the NW–SE to N–S oriented, non-penetrative S_3 planar structures were also observed (Fig. 5C). The S_3 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 marlstones of the Werfen Fm. (Fig. 3H). In more competent rocks like thick-bedded to massive sandstones, the S_3 foliation is nearly missing. Apart from the measured F_3 fold axes, axial undulation of F_2 folds is documented by the girdle of F_2 axes (Fig. 5D). They indicate a later modification of F_2 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 Meliatic Bôrka Nappe and the Gemeric 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 Meliatic rocks, as shown in Fig. 1, was reinterpreted by Lačný et al. (2015). Based on lithology and structural relationships they are now considered to be the frontal elements of the Turňa Unit.

In the present paper, we also reinterpret the position of the Meliatic tectonic inlier (window) near the village of Striežovce (cf. Gaál 1982) in the western part of the investigated region (Figs. 1 and 2). Our view is based on the general structure of this occurrence of Middle–Upper Triassic formations that are surrounded by the upper Lower Triassic Szin marlstones, thus indicating a synclinal structure. Moreover, the Triassic carbonates in the synclinal core do not exhibit the typical "Meliatic" structure with olistolites embedded in Jurassic shales, but fragments of continuous successions can be documented. Consequently, the sequence of metamorphosed Triassic carbonates located in this syncline is now regarded 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 particularity of the Striežovce succession, indicating its more distal passive margin position with respect to other Turňa successions.

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 Szin 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-cylindrical, with doubly-plunging hinges (e.g., the Sása and Striežovce brachysynclines). This might be a cumulative effect 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 Bódvaszilas shales and sandstones. However, 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. (Vozárová & Vozár 1992).

Another borehole DRŽ-1 drilled directly in the Držkovce tectonic window penetrated several alternating slices of Meliatic 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 mélange 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 extremely incompetent evaporites serve as décollement horizons and are often found at the soles of far-travelling cover nappes, where they often incorporate various footwall-derived exotic fragments.

Based on its internal structure, the Držkovce tectonic window 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 D_2 stage.

The two anticlinal macrostructures — the Brusník pericline 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 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 subvertical. 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 S_{01} 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; Árkai 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 Meliatic rocks of the Držkovce and Meliata tectonic windows (see Fig. 2), and from the possibly Turňa Unit metasediments near Hačava village further to the

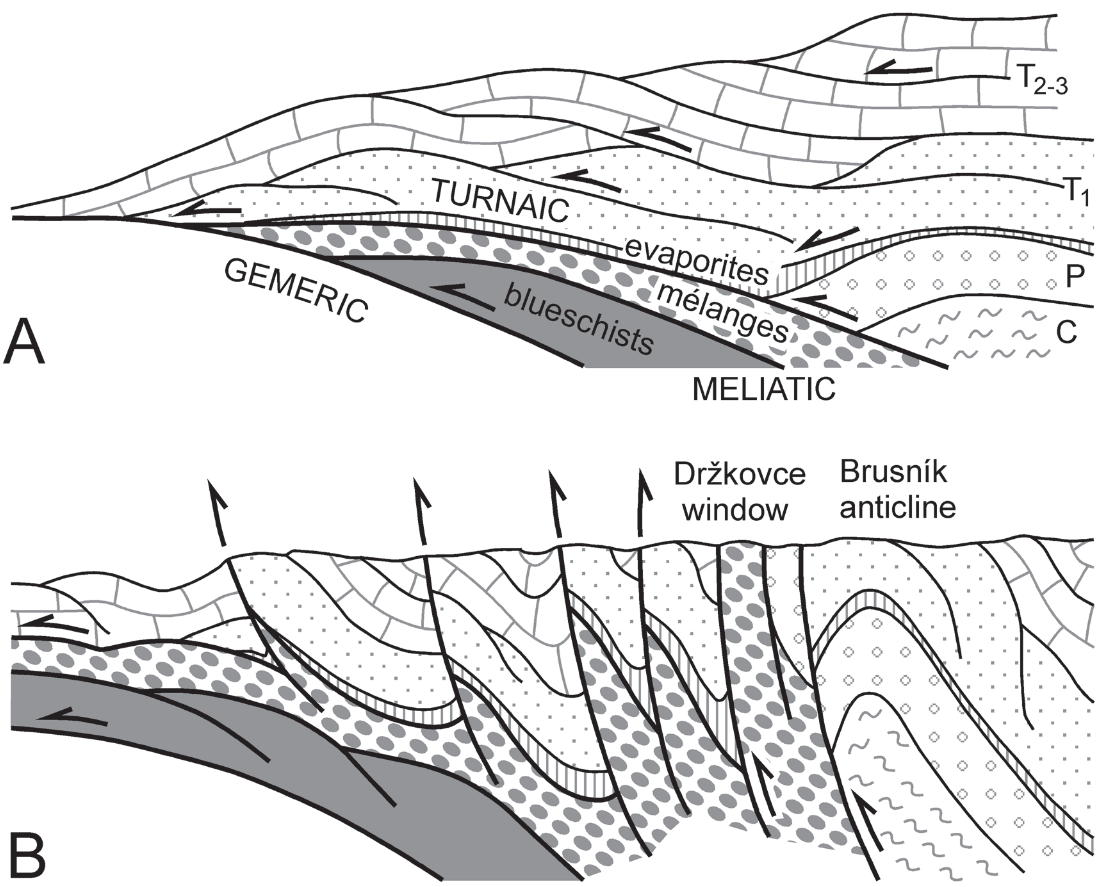


Fig. 6. Scheme of development of large-scale fold and thrust structures of the Turňa Nappe in the examined area. **A** — deformation stage D_1 during the thrust stacking period and growth of the accretionary wedge. **B** — situation after the D_2 stage characterized by out-of-sequence thrusting. Not 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; Kövér 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 Gemeric 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.

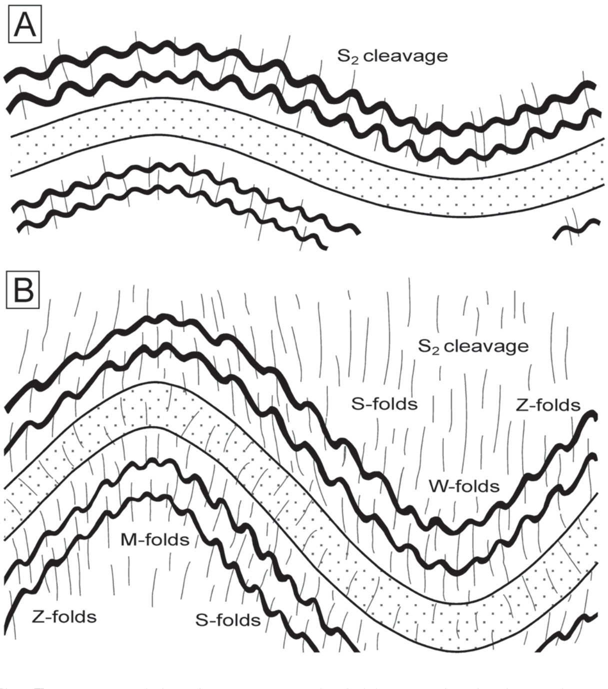


Fig. 7. Two models of outcrop-scale fold types in the investigated area. **A** — fold pattern in the shale-sandstone multilayer of the Bódvaszilas Mb. Initial indistinct S_2 cleavage related to minute folds in shales was rotated around hinges of the younger larger-scale fold limbs of a thick sandstone bed to form a cleavage fan. **B** — Z- and S-type fold tracks in soft marly shales of the Szin Mb. modified by fold tightening and pressure solution along the S_2 cleavage. Both types produce folds with either NW- or SE-dipping axial planes.

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; Kövér et al. 2009; Deák-Kövér 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_3 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 (e.g., Fodor & Koroknai 2000; Hips 2001). It is worth noting that the same orientation of the palaeostress field with the W–E to WSW–ENE maximum horizontal compression axis was also recorded in the Mesozoic to Lower Eocene sediments throughout the Western Carpathians, but the Upper Eocene to Oligocene strata do not contain any record of this event (e.g., Vojtko et al. 2010; Sůkalová et al. 2012).

Geodynamic inferences

In general, the overall structural evolution of the Turňa Nappe with the three distinct deformation stages D_1, D_2 and D_3 as described here is virtually identical with that of the Torna (Martonyi) Unit in the Rudabánya Mts. (Fodor & Koroknai 2000; Kövér et al. 2009; Deák-Kövér 2012) and in the main aspects also with that of the Meliatic units (Mock et al. 1998; Mello et al. 1998; Faryad 1999; Dallmeyer et al. 2008). The overall situation implies that both the Meliatic and Turnaic units were constituents of an accretionary belt that developed during the terminal stages of closure of the Neotethyan Meliata Ocean in the Late Jurassic. This initial phase of the accretionary wedge is recorded by structures of the D_1 deformation stage, mainly the penetrative, bedding-parallel S_1 low-grade metamorphic foliation. Subsequently, the Early Cretaceous collision of the accretionary wedge with the southern Gemeric margin led to its overthrusting and the development of the D_2 fold-and-thrust structures that dominate the present broad-scale structure of the Turňa Unit (Fig. 2).

Notwithstanding the present close structural and metamorphic relationships of the Turňa Unit with the underlying Meliatic rocks, their earliest structural and metamorphic histories appear to be diverse. The rock complexes that are currently affiliated with the Meliaticum represent a very heterogeneous group of units with differing sedimentary, metamorphic and structural histories. Commonly interpreted as a subduction-related mélange (e.g., Dallmeyer et al. 2008), the Meliaticum could be differentiated into at least three particular units (Fig. 8):

1) The Bôrka Nappe (blueschist unit — Leško & Varga 1980; Mello et al. 1998) in the lowermost structural position, directly overlying the Gemeric basement-cover complexes, was affected by HP-LT metamorphism at ca 160–150 Ma (Maluski et al. 1991; Faryad 1995, 1999; Faryad & Henjes-Kunst 1997; Faryad et al. 2005; Dallmeyer et al. 2008) and then exhumed from the subduction channel and incorporated into the accretionary wedge. It is important to note that the Bôrka Unit was derived from a distal continental passive margin, including the Permian clastic sediments, and does not include true oceanic elements (Mello et al. 1998).

2) The chaotic oceanic mélange complexes, also known as the Jaklovce Unit, contains variously sized blocks of basalts, serpentinites, blueschists, acid volcanites, radiolarites of Middle–Upper Triassic and Jurassic age, variegated Triassic shallow- and deep-water carbonates (e.g., the lower unit in the Brusník borehole), and even blocks derived from the Variscan, possibly Gemeric basement (gneisses and amphibolites — Faryad & Frank 2011). All these are embedded in a Jurassic radiolarite-shale-sandstone matrix, whereby the chaotic complexes show a partially sedimentary and partially tectonic origin.

3) The sedimentary unit of Jurassic deep-water deposits with olistostromes and olistoliths of various Triassic carbonates and Ladinian radiolarites, but with poorly represented real oceanic material. This is loosely designated as the Meliata Unit s.s. (e.g., Mock et al. 1998) and can belong to various units of higher order — possibly upper parts of the Meliatic Jurassic complexes occurring below the Turňa-Silica nappes (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 completed 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 D_1, 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 Albian–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,

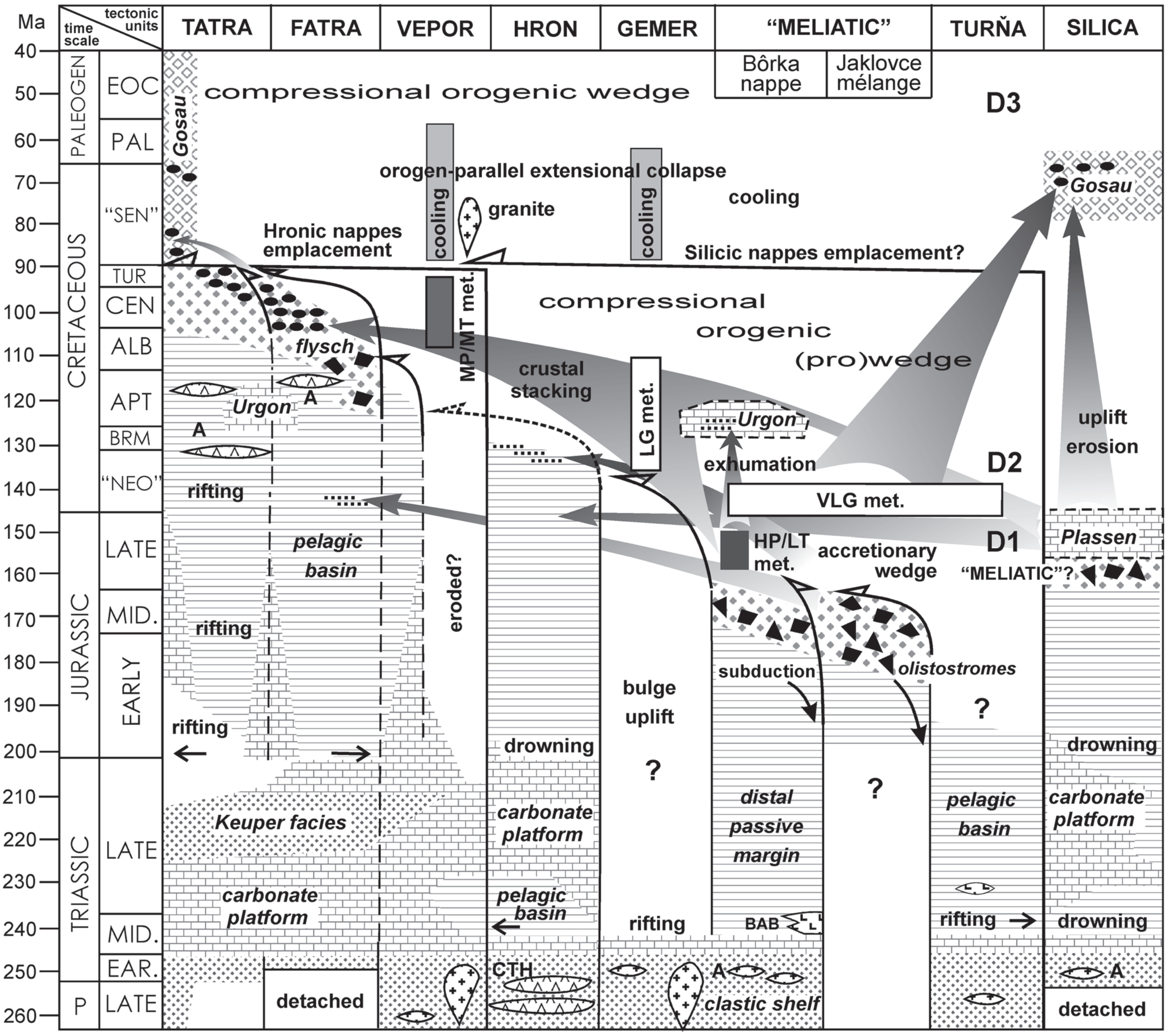


Fig. 8. Synoptic presentation of depositional environments, magmatic events and tectonometamorphic processes of tectonic units that are discussed in the text. Magmatic rocks: **A** — alkaline; **CTH** — continental tholeiites; **BAB** — back-arc basalts. Black asymmetrical arrows indicate main thrusting events. Dispersal pathways of clastic material derived from ophiolite and blueschist complexes, as well as from vanished temporary carbonate platforms, are shown by thick grey-shaded arrows. Note that tectonic units are arranged according to their present structural position from the lower (left) to the upper (right). This does not necessarily imply their original palinspastic relations, however. Note also that the original position of the presently completely eroded carbonate platforms (Plassen, Urgon) is not constrained by any direct data. Time scale according to www.stratigraphy.org.

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-Aggtelek 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 (Gemeric, 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; Vojtko 2000; Gawlick et al. 2002; Havrila 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 reworked 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 olistostromatic 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 (Sýkora & 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. Krische 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 (Meliaticum s.l.) overlie directly and primarily the Gemeric 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; Csontos & Vörös 2004; Dallmeyer et al. 2008; Froitzheim et al. 2008; Schmid et al. 2008; Kövér et al. 2009; Kövér & 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 D_1 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 S_{01}. At the same time, the wedge incorporated Meliatic ophiolite fragments and various mélange complexes, as well as the exhumed HP/LT metamorphic slabs derived from the subducted distal passive continental margin (Bôrka 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 D_2. 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 folds 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 registers a "cross" folding process with WSW–ENE oriented horizontal compression. Its expressions are rather weak, represented by approximately N–S trending kink bands and occasional spaced cleavage. The D_3 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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