Original paper

Deformation pattern of the Lower Triassic sedimentary formations of the Silicic Nappe: Evidence for dynamics of the Western Carpathian orogen

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The Lower Triassic formations of the Silicic Unit were studied by structural geology methods to unravel its deformation history and chronology of nappe transport. The nappe sheet of this unit is the highest representative thin-skinned thrust in the Western Carpathians. The Silicic Unit spreads in the broader area of the Variscan consolidated Gemeric and the Veporic crystalline basements. Geological and palaeotectonic evidence indicate that the Silicic nappe pile is more than one km and at some places up to 3 km thick. The nappe is abundant in the inner zones of the Western Carpathians and overlaps all other structural units in the area, in particular it covers the margin of the Gemeric Unit. Based on the structural analysis, geometry and overprinting criteria of secondary planar structures (cleavages or fold axial surfaces) and fold axes indicate the presence of three main deformation events. Generally, the first group of structures is related to ≈ W–E shortening (AD_1), which is interpreted in association with closure of the Meliata Ocean. The younger direction of the Silicic nappe system shortening (AD_2) shows top-to-the-NNW thrusting and is related to the Early to Late Cretaceous Eoalpine convergence. This stage also comprises folds with steep north dipping axial surfaces and occasionally also flat-lying axial surfaces forming fan-like structure of fold axial planes. The last observed structures refer to the W–E shortening (AD_3) characterised by the symmetric gentle to open folds with subvertical axial surfaces locally with few pronounced top-to-the-east asymmetries.

Keywords: Western Carpathians, Silicic nappe, thrusting, folding, tectonic transport
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1. Introduction

Nappes or tectonic nappes, discovered towards the end of 19th century are common geological structures in orogenic belts (e.g., Price and McClay 1981), particularly in the Alps (e.g., Lugeon 1902; Termier 1906; Argand 1916; Tollmann 1973; Trümpy 1980; Escher et al. 1993; Froitzheim et al. 2008; Pfiffner 2014) and Carpathians (e.g., Andrusov et al. 1973; Plašienka 2018). Geological studies often refer to a "nappe theory", and the kinematics and vectors of nappe movement is a solvable topic. However, the physical mechanisms of nappe formation and its movement are still not well understood. Several definitions of a nappe have been proposed, for example, "A nappe is a rock packet not in its place, resting on a substratum that is not its original one" (Termier 1922). Two end-member types of nappes are commonly distinguished: (1) fold nappes correspond to large-scale recumbent folds with stratigraphic inversion and amplitudes exceeding several kilometres; while (2) thrust sheets correspond to allochthonous sheets with a prominent shear or thrust zone at their base. The thrust sheets show folding of the internal nappe body, especially in its lower portion, although these folds do not show prominent overturned limbs (e.g., Price and McClay 1981; Epard and Escher 1996).

The inner zone of the Central Western Carpathians has an imbricated structure with thick-skinned units overlain by thin-skinned nappes. The Mesozoic sedimentary sequences in detached nappe positions are located mainly on top of the thick-skinned Gemeric Unit (Fig. 1). The rocks of the Meliata accretionary wedge, are represented by Permian siliciclastic deposits, Triassic limestones deposited on the thinned continental margin, and blueschist facies metabasalts (cf. Faryad 1995). The latters were affected by HP/LT metamorphism and traditionally are

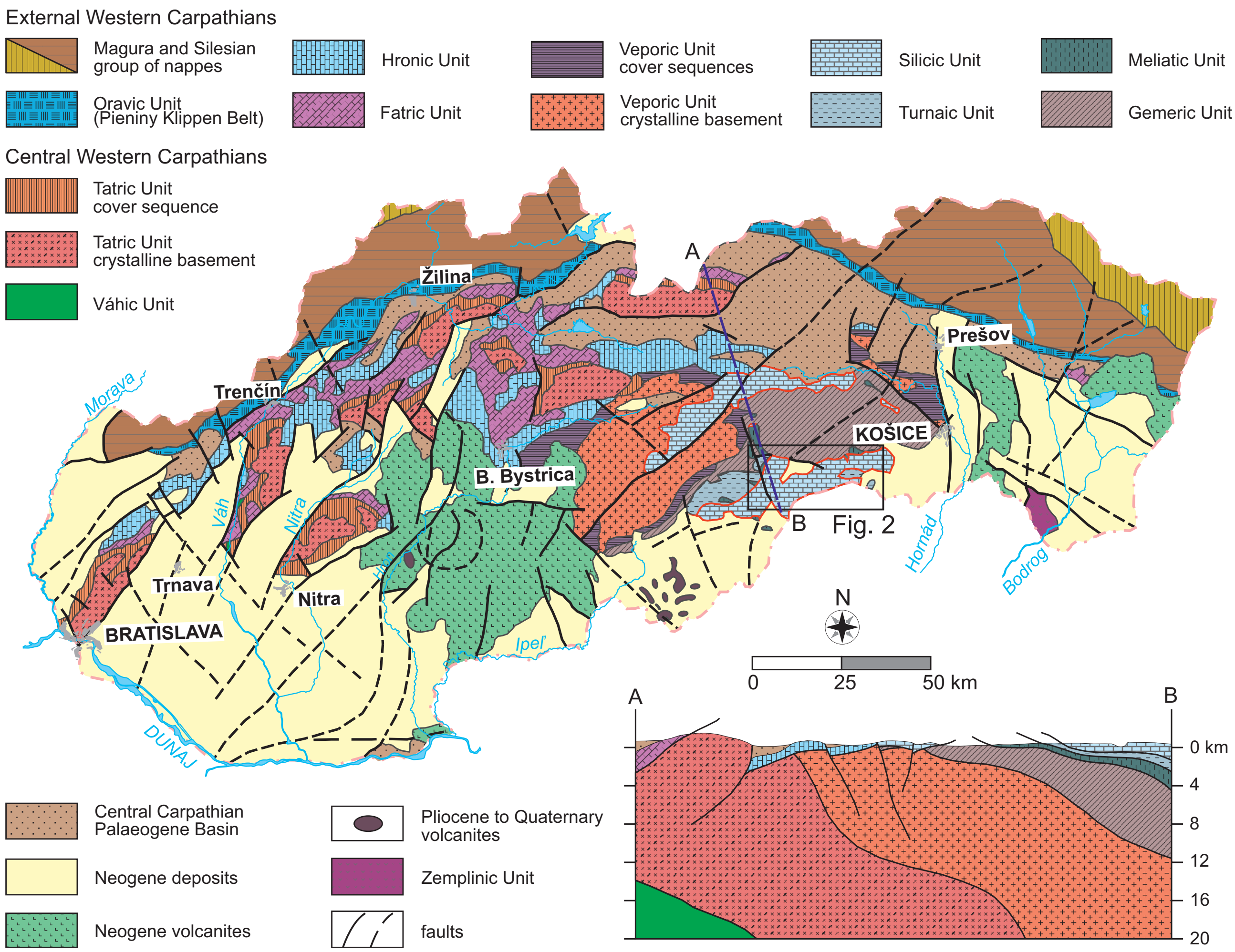

Fig. 1 Tectonic map and idealised cross-section of the Slovak part of Western Carpathians with marked study area by a black rectangle (according to Biely et al. 1996). Note: The Silicic Unit is highlighted by red boundaries.

referred to as the Bôrka nappe (Faryad 1995; Mello et al. 1998; Faryad et al. 2005; Dallmeyer et al. 2008). The Meliatic Unit s.s. is composed of the Jurassic mélange with huge olistostromes with a block of various Triassic carbonate rocks, ophiolite- and blueschists-bearing rocks (e.g., Kozur and Mock 1997; Mock et al. 1998; Ivan 2002). The Jurassic mélange and the HP/LT metamorphosed rocks are tectonically overlain by Upper Palaeozoic to Triassic shales, carbonates passing upwards to pelagic deposits (Turnaic nappe). The Meliata accretionary wedge and the underlying Gemeric Unit are tectonically overlain by the extensive Silicic nappe system (Mello 1979). The Silicic Unit is structurally the highest nappe system in the Central and Inner Western Carpathians, and it consists of several isolated occurrences.

The whole Meliata accretionary wedge overcame the Late Anisian rifting phase and drowning of the Lower Anisian carbonate ramp and platform, which have never been restored. The process is commonly interpreted as the continental breakup stage and onset of the Neotethyan (Meliata) Ocean. The Pelsonian rifting is also documented in the sedimentary record of the Silicic Unit. However, the Lower Anisian carbonate ramp was restored in the Ladinian stage and practically lasted until the end of the Triassic period. The Meliata Ocean was closed by the Jurassic subduction and this process resulted in the formation of an accretionary wedge and its obduction over the Gemeric Unit during the Late Jurassic (150–160 Ma; Maluski et al. 1993; Dallmeyer et al. 1996; Faryad and Henjes-Kunst 1997a,b; Plašienka 2018).

In this work, we focus on the analysis of the Silicic nappe system in south-eastern Slovakia, which represents one of the rootless nappe structures in the Central Western Carpathians (CWC). Although the nappe contacts among the other CWC nappe systems, Meliatic, Turnaic, and Silicic, have been relatively well understood, the age and direction of their transport remain a matter of discussion. It has been proposed that the Silicic nappe has been displaced southwards (e.g., Kozur and Mock 1973; Andrusov 1975: Grecula 1982; Mello et al. 1997), northwards (e.g., Hók et al. 1995; Rakús 1996; Lexa et al. 2003; Plašienka 2018) or had a polystage evolution (e.g., Reichwalder 1982).

The principal aim of this contribution is to summarise, evaluate, and interpret a large quantity of structural data collected from the Silicic nappe, and to present palaeotectonic synthesis on its thrusting and internal deformation. In particular, the interplay between the superficial processed and their deep-seated tectonometamorphic expressions is a subject of the presented analysis followed by interpretation in terms of regional tectonic evolution during the Mesozoic era.

2. Geological setting

The Western Carpathians are the northeasternmost segment of the European Alpine Orogen and are divided into Internal, Central, and External Western Carpathians (e.g., Andrusov et al. 1973; Plašienka et al. 1997a; Plašienka 1999; Froitzheim et al. 2008). Some authors used a simplified model of division into External and Internal Western Carpathians (e.g., Hók et al. 2014). The Central Western Carpathians consist of stacked (1) thick-skinned crustal-scale basement nappes/units (Tatric, Veporic, and Gemeric), incorporated into the Late Cretaceous collisional wedge, and (2) overlying thin-skinned nappes (e.g., Andrusov et al. 1973; Plašienka et al. 1997a; Froitzheim et al. 2008). The thick-skinned nappes are composed of Variscan crystalline basement and Upper Palaeozoic to Mesozoic cover sequences while the thin-skinned nappes are represented by Mesozoic (mostly Triassic carbonatic) sedimentary formations.

Individual and structurally independent tectonic units of the inner zones of Central Western Carpathians are listed from structural footwall to hanging wall (Fig. 1): (1) the Veporic Unit is a thick-skinned nappe and containing the Variscan high-grade basement and cover, which was also affected by an up to amphibolite facies Cretaceous overprint (Vrána 1980; Janák et al. 2001; Jeřábek et al. 2008). (2) the Ochtiná nappe is represented by low- to intermediate-grade metamorphosed Carboniferous sediments (Novotná et al. 2015) and is assigned to the thick-skinned nappe system of the Gemeric Unit. It is composed of Lower Palaeozoic volcano-sedimentary sequences overprinted at up to amphibolite facies conditions during Variscan orogeny and, together with its cover, also at greenschist facies conditions in the Cretaceous (Faryad 1997; Petrasová et al. 2007), (3) the Bôrka nappe with blueschist facies metamorphism and the Meliata tectonic mélange and Turnaic Unit with Barrowian anchizonal metamorphosis overlays the Gemeric Unit (Faryad 1995; Mello et al. 1998; Faryad et al. 2005; Dallmeyer et al. 2008), and (4) the Silicic Unit represents unmetamorphosed thin-skinned nappes dominated by Triassic carbonate platform sediments (Fig. 2).

2.1. The Gemeric crystalline basement

The lowermost part of the southern zone is composed of the thick-skinned continental Gemeric Unit with its sedimentary cover (Fig. 2). The Gemeric sheet overrides the Veporic Unit along the thrust zone known as the Lubeník–Margecany fault (e.g., Plašienka et al. 1997b). The Gemeric Unit is the uppermost Central Western Carpathian thick-skinned nappe system with affinities to the Upper Austroalpine basement units in the Eastern Alps (Gurktal and Graz nappes) and partly to the Grauwackenzone underlying the Northern Calcareous Alps (cf. Neubauer et al. 2000). The pre-Alpine, Variscan metamorphosed crystalline basement is composed of the Lower Palaeozoic to early Upper Carboniferous mostly low-grade metasediments and metavolcanics intruded by small bodies of Permian granites. Structurally this basement is closely confined to lithologically and metamorphically similar Upper Palaeozoic sedimentary succession (Vozárová and Vozár 1988; Faryad 1991; Plašienka et al. 1997a).

The basement consists of three principal subunits that differ in lithology and metamorphic grade. Structurally, the lowermost basement contains Palaeozoic volcanosedimentary complex with dominant felsic volcanism known as the Gelnica Subunit, which forms volumetrically a major part of the Gemeric basement. The lowermost portion of the Gelnica Subunit comprises Ordovician to Silurian fine-grained metagreywackes and phyllites, graphitic phylites with lydite layers, occasionally with lenticles of metacarbonates (Vozárová et al. 1999). The sedimentary succession also contains felsic volcanic and volcaniclastic rocks. Towards the overlying strata metasediments are characterised by laminated chlorite-sericite, graphite phyllites and sporadic metacarbonates, ankerite and siderite ore bodies with intercalation of massive felsic volcanic and volcaniclastic rocks Silurian to Early Devonian age (e.g., Cambel et al. 1990; Vozárová et al. 1999). The regional metamorphic conditions indicate temperatures between 350 and 400 °C and pressures of 2.5–3.5 kbar (Faryad 1992, 1994), which are overprinted by thermal metamorphism at 450–550 °C and ≈ 2 kbar (Faryad 1992).

The higher metamorphosis (amphibolite facies) is reported from the Klátov Subunit (Spišiak et al. 1985; Faryad 1990), which is thrust onto greenschist facies mafic rocks and metapelites of the Rakovec Subunit (Andrusov 1958; Bajaník et al. 1981). The Klátov Subunit overcame Variscan metamorphic condition at 440–480 °C and 6–8 kbar and the Rakovec Subunit at 350–430 °C and 4–5 kbar (Spišiak et al. 1985; Vozárová 1993; Faryad and

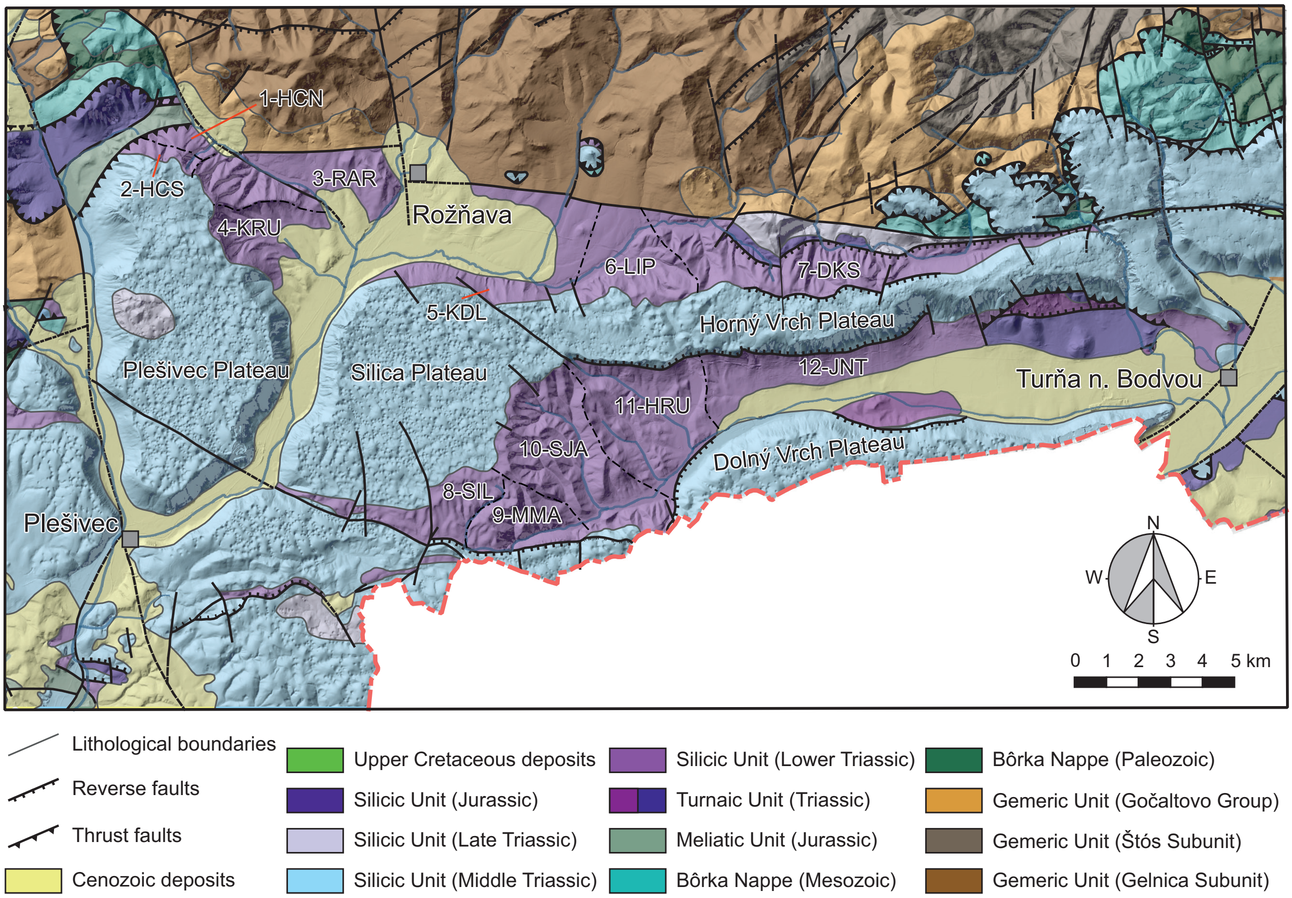

Fig. 2 Tectonic structure of the Slovenský kras Mts., the position of investigated sectors with lined lines and sites marked by the red cross and numbers where structural measurements were carried out (according to Bezák et al. 2008; Mello et al. 2008).

Bernhardt 1996). These subunits were derived from the oceanic crust and the ophiolite suite is still preserved. The ophiolite-bearing succession was included in the newly redefined Zlatník Group (Ivan and Méres 2012). The tectonic contact between these units is Variscan instead of Alpine. In the northern portion of the Gemeric Unit, the Rakovec and Klátov subunits are lying on the Gelnica Subunit.

In the southeastern part, the Gelnica Subunit is unconformably overridden by the Štós Subunit, which is considered to be similar to the Rakovec Subunit (Bajaník et al. 1981). However, the mafic volcanic rocks are absent. The Štós Subunit contains a monotonous sedimentary sequence of laminated sericite and sericite-chlorite phyllites with intercalation of metasandstones and quartzose phyllites of the assumed Early Carboniferous age.

The already consolidated Gemeric crystalline basement was discordantly sealed by Upper Carboniferous metamorphosed flysch sequences (Dobšiná Group; Bajaník et al. 1981; Vozárová and Vozár 1988) overlain by Permian siliciclastic red-beds type deposits accompanying by felsic volcanic rocks (Gočaltovo and Krompachy groups; Bajaník et al. 1981). The sedimentation terminated by the evolution of Upper Permian evaporites and Lower Triassic siliciclastic to carbonatic rocks. The Gemeric Unit represents the stack parts of the former passive margin of the Meliata Ocean.

2.2. Mesozoic Meliata Accretionary Wedge

The Variscan Gemeric crystalline basement and its cover are structurally overlain by Permian-Jurassic metamorphosed units deposited on the continental margin or oceanic/paraoceanic crust – Bôrka nappe with blueschist facies metamorphism and the Meliata tectonic mélange with Barrowian anchizonal metamorphosis (Fig. 2). The unit is formed by Jurassic deep-water clastic complexes with radiolarites, olistostromes, mélanges and ophiolitic bodies, which crops out in the western parts of the Slovak Karst area. The most distinctive feature of the Meliatic Unit is that the Lower Anisian platform carbonates show evidence of a Pelsonian unconformity, and Upper Anisian and younger pelagic deposits. The original assumption of a Triassic Meliata Ocean was based on these pelagic Triassic strata and other sites still provide evidence, along with other features, for the existence of a Triassic oceanic realm that persisted up to Late Jurassic times. Hence, the Meliata Ocean in the Western Carpathian realm is assumed to have existed from the Middle Triassic to the early Late Jurassic.

The upper part of the Mesozoic nappe stack is composed of the Carboniferous to Upper Triassic anchimetamorphosed units deposited on the continental crust (Turňa Unit or Torna Unit, respectively). It is overthrust by the Upper Permian to Jurassic non-metamorphosed Silicic Unit deposited also on the continental crust (Fig. 2). The Turňa nappe pile is defined as a rootless nappe system consisting of several partial units comprising mainly slope to basinal hemipelagic sediments. The Turňa-like elements were also suggested to be present in the Alps, together with the Meliatic Florianikogel Unit.

The stratigraphic succession of the Turňa Unit includes the Carboniferous Turiec Formation, which is related to the Szendrő Phyllite Formation and the Hochwipfel Flysch of the Carnic Alps. Permian continental sediments and Lower Triassic siliciclastic deposits are overlain by Middle to Upper Triassic predominantly open marine carbonate succession. Definition of the Turňa Unit includes Lower Anisian platform carbonates (mainly Honce Formation, which is most probably metamorphosed equivalent of the Steinalm Limestone and exclusively pelagic limestones from the Late Anisian on as Žarnov, Nádaska, Reifling, and Pötschen limestones. Carnian sediments, including shales, marlstones, sandstones and, locally, volcanics are also typical members and formations of the unit (Lačný et al. 2016, 2018).

Consequently, the boundaries between the Meliatic and Turnaic units are sometimes uncertain. At most places, the Turnaic Unit shows evidence of low-grade, but relatively high-pressure metamorphism (about 7 kbar).

These aforementioned tectonic units were displaced from their original position during Late Jurassic to Late Cretaceous times (Andrusov 1958; Maheľ 1986; Plašienka et al. 1997a, b; Plašienka 1999, 2018; Lexa et al. 2003).

2.3. Superficial nappe system of the Silicic Unit

The nappe sheet of the Silicic Unit (firstly defined by Mello 1979) is the highest representative thin-skinned (superficial or cover) thrust unit in the Central (*sensu* Plašienka 2018) or Inner (*sensu* Hók et al. 2014, 2019) Western Carpathians (Fig. 2). The Silicic Unit spreads in the broader area of the Variscan consolidated Gemeric and the Southern Veporic crystalline basements (Drienok, Muráň, Vernár, Stratená, and Silicic nappes; Plašienka 2018; Vojtko 2000) and Internal Western Carpathians (Silica–Aggtelek nappes, Szőlősardó and Bódva nappes in the Aggtelek Karst and Rudabánya Mountains of northern Hungary; cf. Kövér et al. 2009; Haas et al. 2012). The Silicic nappes can be correlated with the Upper Tirolic and/or Juvavic nappes of the Northern Calcareous Alps. Geological and palaeotectonic evidence refers to that the Silicic nappe pile is more than one km and, in some places, up to 3 km thick, but areally abundant in the inner zones of the Western Carpathians, especially forming the margin of the Gemeric Unit. The Silicic Unit is composed of sedimentary complexes of the Late Permian to Late Jurassic age and dominated by extensive Middle to Upper Triassic carbonate platforms. Most of the geological and palaeotectonic evidence confirm that this thin, but spatially extensive nappe body has been transported top-to-the-north over the underlying Bôrka-Meliata-Turňa Mesozoic accretionary wedge to several tens of kilometers as a relatively homogeneous thrust sheet (e.g., Hók et al. 1995; Plašienka 1999, 2018).

The Silicic Unit forms thrust nappes, detached at the sole of a thick rigid Triassic carbonate complex, usually along the Upper Permian–Lower Triassic evaporitic horizon called the Perkupa Formation. Moreover, at the base of the Silicic nappes in places, slices of Meliatic oceanic rocks were found, incorporated into evaporite mélanges. The sole of the unit is overlain by Lower Triassic sandstones and shales (Bódvaszilas Formation) and marlstones to limestones (Szin Formation) with very rare felsic volcanics in the (Drienok–Muráň–Vernár nappes). The lowermost part of the investigated Lower Triassic sequence is formed by the siliciclastic deposits, predominantly comprising variegated siltstones and sandstones of the Bódvaszilas Formation (Induan). The siliciclastic rocks are occasionally micaceous, and they are monotonous and have a flysch-like character (alternation of mostly gradation-layered sandstones with shales). Hieroglyphs, traces of raindrops, and frequent cross-bedding occur on the sandstone and shale bedding planes.

The upsection of the sequence is composed of considerable bioturbated marlstone, marly limestone to limestone of the Szin Formation (Olenekian), occasionally with unknown macrofauna. In the lower part of the sequence, sandy claystone, sandy limestone, and sandstone of the Silická Jablonica Member with the Early Olenekian age crops out mainly in the southern slopes of the Silická Planina Plateau. On the contrary, the oolitic sandy limestones with gastropods (“Gastropodenoolit” – Rakovnica oolitic limestone) crop out in the northern and eastern edge of the Plešivecká Planina Plateau.

In an upward direction, the formation continuously passes to black thick-bedded Gutenstein Limestone of the Anisian age. The contact of the Szin Formation with the overlying Middle Triassic carbonate complex sequence displays distinct upsection changes from siliciclastic deposition towards the onset of the carbonate ramp composed of the Anisian carbonate ramp (Gutenstein Formation) and platform (Steinalm Formation). These carbonates build-ups were partly destroyed by a significant Pelsonian rifting event, which led to the formation of intra-shelf basins filled with hemipelagic nodular limestones and resedimented carbonates (Schreyeralm, Reifling, Nádaska, Raming formations). During the Late Ladinian to Early Carnian, carbonate platform complexes with typical shallow marine Wetterstein Formation predominated. Thin intercalations of altered tuffites are known from the Ladinian succession. Middle Carnian-age siliciclastic turbidites also occur locally (Lunz and Reingraben formations with deeper marine Leckogel Formation). During the Late Triassic, barrier reefs grade into back-reef lagoonal flats (Tisovec, Dachstein, Hauptdolomit, Bleskový Prameň formations) were formed.

In the Hungary (Aggtelek Karst), Wetterstein to Tisovec Triassic platform carbonates are overlain by Upper Triassic slope and basinal pelagic limestones and marlstones (Aflenz, Pötschen, Hallstatt, Zlambach formations). The southernmost units, presumably belonging to the Szőlősardó and Bódva nappes are marked by the prevalence of pelagic facies already in the Middle Triassic (after the Pelsonian rift event), such as the Ladinian Hallstatt-type Bódvalenke limestone and cherts deposited near the CCD (Szárhegy Formation). This facies indicates an area of transition to the Meliata Ocean.

The Jurassic members are poorly preserved, and their overall thickness do not exceed more than several tens of metres. After the earliest Jurassic hiatus, the Hierlatz and Adnet limestones were deposited on basin highs on top of the Upper Triassic carbonates. In basinal areas, hemipelagic marly to cherty limestones to marlstones of the Allgäu Formation were deposited. Middle to Late Jurassic subsidence led to the deposition of deep-water shales and radiolarites with some terrigenous input as an equivalent of the Alpine Ruhpolding Radiolarite Group (Gawlick and Frisch 2003; Gawlick et al. 2009). The youngest dated sediments of the Silicic Unit are Oxfordian in age. The Silicic nappe system is correlable with the Juvavic nappes (Upper Austroalpine) based on structural position (overriding of Meliata imbricates) and lithostratigraphy.

Palinspastic reconstruction of the Permian to Jurassic sequences in the individual nappes of the Western Carpathians, placing the original depositional area of the later Silicic nappe on the northern edge of the Meliata Ocean, prevail (e.g., Kozur and Mock 1973; Reichwalder 1982; Michalík 1993; Gawlick et al. 1999; Gawlick and Missoni 2015). This position is mainly based on the lateral changes of Triassic facies. Such arrangement of the depositional areas assumes a southward transport of the Silica-like thrusts onto the Meliatic and Turnaic units. However, southwards displaced nappe is in some contradiction with the direction of transport of other nappe systems in the Western Carpathians lying to the north of the presumed position of the Meliata accretionary wedge. To the contrary, the structural pattern of the tectonic nappes lying beneath the Silicic nappe require northwards displacement (cf. Hók et al. 1995; Rakús 1996; Plašienka 2018), which is in line with nappe polarity of other nappe systems in the Western Carpathians. In many cases, the detachment proceeded mostly in ductile or semiductile layers like the Upper Permian schist formations with frequent evaporite intercalations and schistose Lower Triassic sedimentary sequences. Owing to intense Alpine orogeny most of the Mesozoic sequences of the so-called Silicic Unit are in an allochthonous position and are lying on the different substratum. Further to the south in NE Hungary, the Silicic (aka. Szilice or Aggtelek) nappe is lying on the metamorphosed Telekesoldal complex and evaporite with ophiolite fragments. The Silicic nappe that makes up the Aggtelek Mountains is in the highest structural position. In this area, the Silicic Unit is also represented by the non-metamorphic Bódva nappe, which is thrust onto the Perkupa evaporite succession and is overridden by the metamorphosed series of the Torna nappe and the Meliata-type Telekesoldal nappe (e.g., Less 2000; Less and Mello (Eds.) 2004; Kövér et al. 2009; Haas et al. 2012). The nappe stack is southeast to south verging and the thrusting was carried out by one (Hók et al. 1995; Less 2000) or two phases (Kövér et al. 2009). Moreover, Less (2000) also discussed the northward subduction and in some works the thrusting was considered as Miocene in age (e.g., Grill et al. 1984; Less 2000). However, the structures of thrusting are disrupted by the Miocene-age Darnó Fault and sealed by the Oligocene deposits on both sides (cf. Kövér et al. 2009; Haas et al. 2012).

3. Methods

For measured geometric characteristic of folds, analytic geometry and stereographic projection were employed for the estimation of the orientation of the fold axis and axial surface (see Lisle and Layshon 2004). Fold axes and axial surfaces were constructed from measured fold limbs using the π pole method (construction of β axes of fold), or by direct measuring of fold axes at outcrops (e.g., Ramsay and Huber 1987; Lisle and Layshon 2004). For the computation of fold axis from measured fold limbs as an intersection of planes or fold axial surfaces as a plane bisecting inter-limb angle between two planes (fold limbs) was used GeolCalc software (developed by R. Vojtko) and visualised by Stereonet software (developed by R. Allmendinger; cf. Allmendinger et al. 2012; Cardozo and Allmendinger 2013).

The deformation regime operating during folding was determined by an analysis of geometrical orientation data of bedding planes, fold axes, and axial surfaces. These

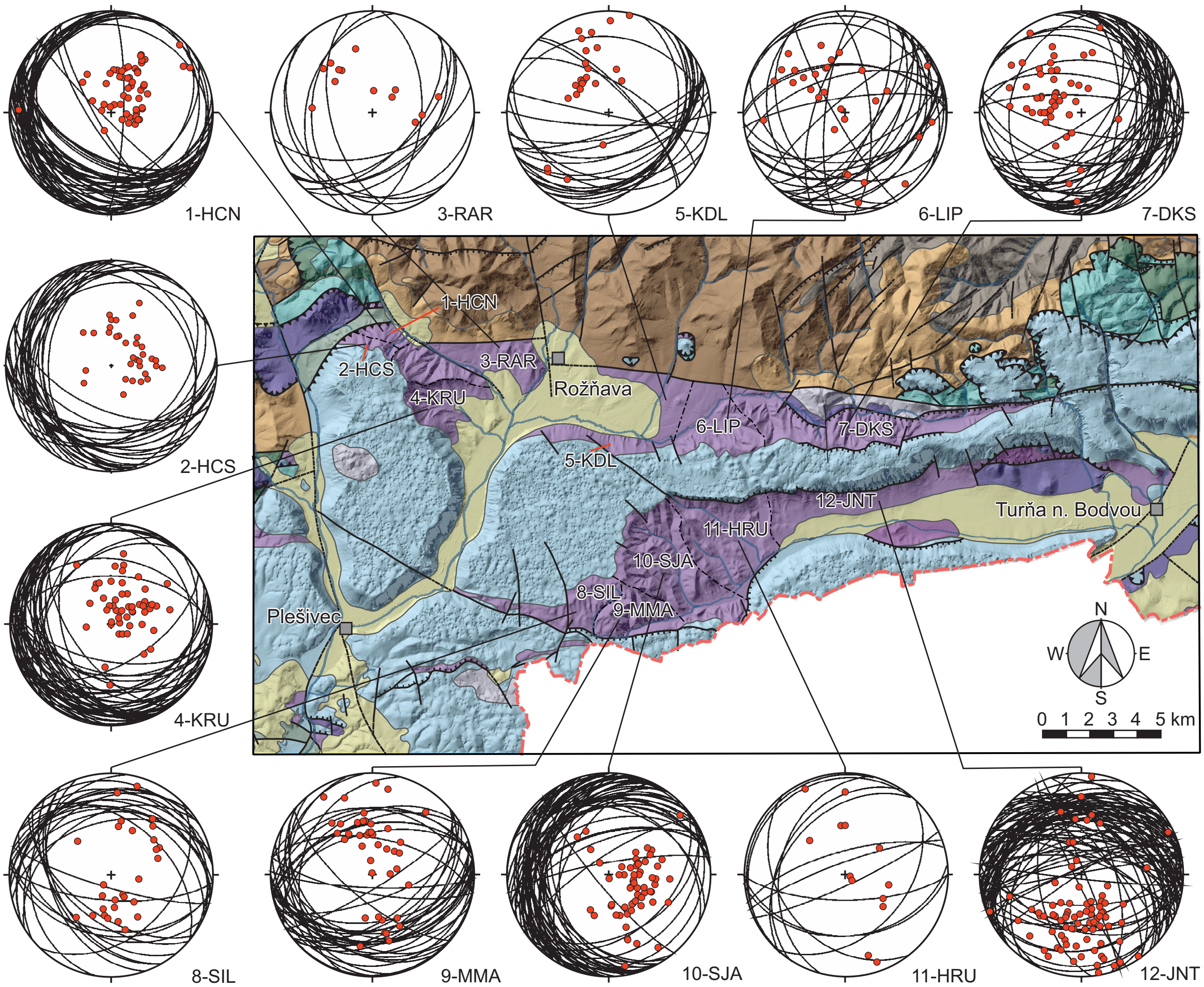

Fig. 3 Tectonic map with bedding planes S_0 (great circles and poles of planes| measured in Lower Triassic sandstones, shales, marlstones, and occasionally well-bedded carbonates (Lambert projection, lower hemisphere).

basic geometrical characteristics of folds reflect the orientation of the principal constriction and elongation direction in relatively simply folded regions. A classification of folds based on the dip of axial surfaces and the plunge of the hinge line was used. This fold terminology is useful to characterise the geometric position of a fold in space and was unified by Fleuty (1964).

The facing of a folding system refers to the geographic direction of the younging (shown with an arrow) of the long limbs of its parasitic folds. In a folding system, such as the one presented below, the facing is changing as one crosses major fold hinges. Indeed, from west to east, this folding system is facing west upward, then east downward, then west upward, and east. The concept of vergence refers to the general sense of shear involved in the development of asymmetric folds. The fold systems shown below are verging east as the asymmetry is the result of a shearing top-to-the-east.

Finally, it should be noted that any planes (surfaces) are marked as "*S*" with indexes in subscript that represent the order of planar structure. For example, S_0 means sedimentary bedding (primary planar structure), and S_1 to S_n represents secondary tectonic foliation. The same classification was used also in the case of lineation "*L*" and *F* – fold structures. In the following text, unified deformational stages used to sketch the interpretation of structure evolution and relative chronology were designated as "*AD*" – Alpine deformation phase. The use of these symbols was important for the readability of the described deformation phases and their structures.

The spatial distribution of the principal strain axes was calculated using the Bingham axial distribution. Its most common use is in the cylindrical best-fit determination of the fold axes. The routine works by calculating the orientation tensor from the direction cosines of the individual measurements and then calculating the eigenvalues and eigenvectors to get the principal axes of the tensor where X – principal maximal strain axis (elongation); Y – intermediate strain axis; Z – principal minimal strain axis (shortening) (cf. Fisher et al. 1987; Allmendinger et al. 2012; Allmendinger 2019).

Field structural documentation was carried out on 80 sites, which were divided into 12 sectors, covering the entire area of the Silicic nappe (Fig. 2). These sectors include the northern and eastern parts of (1) the Plešivec Plateau, (2) northern and (3) southern rims of the Silická planina and Horný vrch plateaus. The deformational structures were documented exclusively in the Lower Triassic formations of the Silicic nappe (Bódvaszilas, Szin, and Silická Jablonica formations or members, respectively) as these weaker horizons represent the sole of the nappe.

4. Structural observations

4.1. Primary structures

In the north-western area (Plešivecká Planina Plateau), bedding (S_0) is mostly subhorizontal or gently dipping predominantly to the south-west except for steeply inclined fold limbs in the vicinity of fold structures (Fig. 3 – HCN, HCS, KRU). The dispersion of poles of S_0 indicates a complex folding pattern related to several phases of folding interference. At some places, bedding (S_0) is gently to moderately dipping to the west and east-southeast (Fig. 3 – RAR).

On the northern side of the Silická planina Plateau and Horný vrch Plateau, the primary structures S_0 can be placed in two sets. The NNE–SSW striking of bedding S_0 with prevailing inclination ESE is dominant and measured bedding planes S_0 with W–E strikes were less frequent (Fig. 3 – KDL, LIP, DKS). However, the striking of bedding planes changes systematically through the sedimentary succession from the bottom to the top. The bottom portion of the sequence is characterised by the prevailing southward dip direction, which is rarely alternating with northward dipping S_0. In general, the succession has a monoclinal structure, which is in several places disrupted by asymmetric fold with northward vergence. Towards the upper-lying strata, the bedding (S_0) quickly changed, with the dip direction eastward and gentle to immediate dip angle (Fig. 3 – HRU, KDL, LIP, DKS). Predominantly W–E striking bedding with dipping on both sides again depicts the uppermost portion of the sedimentary succession less than 50 metres below the carbonate complex.

South of the Silická planina Plateau and Horný vrch Plateau, the general strike of bedding planes (S_0) is a W–E direction (Fig. 3 – SJA, HRU). However, the NW–SE to N–S strikes can also occur in minority. The dipping of bedding planes (S_0) varies from gently to moderately, occasionally it is also steep. The high dispersion of bedding planes (S_0) orientations is linked to semiductile deformation by flexural slip folding. The poles of bedding (P_0) are concentrated in great circles, which indicates folding.

4.2. Deformational structures

The high dispersion of the poles of bedding planes is related to semiductile deformation by folding. The outcrops comprise very nice examples of asymmetric and symmetric cylindrical to non-cylindrical (curvilinear), double plunging folds (Fig. 4). The folds are open to tight with axial surfaces from gently to steep plunging folds. Based on the measured and recalculated axial planes and fold axes, it is possible to divide the deformational structures into three deformational groups (Tab. 1).

The first, oldest, group is characterised by deformation (AD_1), which is responsible for the formation of symmetric and asymmetric F_1 open to close folds with the moderately to steep dipping of axial surfaces (S_1) eastward

Tab. 1 Spatial distribution of the principal strain axes calculated using the Bingham axial distribution method: Note: X – principal maximal strain axis (elongation); Y – intermediate strain axis; Z – principal minimal strain axis (shortening).

No.	Code	AD1			AD2			AD3		
		X	Y	Z	X	Y	Z	X	Y	Z
1	HCN	125/71°	006/11°	267/16°	109/75°	261/14°	353/07°	323/82°	175/07°	085/04°
2	HCS	053/75°	186/11°	279/11°	–	–	–	351/79°	182/11°	092/02°
3	RAR	135/68°	025/08°	292/21°	354/67°	242/09°	148/21°	242/53°	141/08°	045/36°
4	KRU	–	–	–	118/67°	268/20°	002/11°	005/54°	203/35°	107/9°
5	KDL	060/42°	154/04°	248/48°	336/89°	256/01°	146/01°	–	–	–
6	LIP	113/69°	019/01°	289/21°	071/47°	234/42°	332/9°	159/82°	347/08°	257/01°
7	DKS	304/74°	170/12°	077/11°	275/63°	097/27°	007/01°	–	–	–
8	SIL	167/66°	020/20°	285/12°	147/58°	280/23°	019/21°	–	–	–
9	MMA	–	–	–	258/43°	079/47°	348/01°	278/43°	008/01°	098/47°
10	SJA	082/52°	343/07°	247/37°	208/64°	080/16°	344/19°	063/80°	189/06°	280/08°
11	HRU	–	–	–	344/66°	248/03°	157/24°	–	–	–
12	JNT	317/42°	190/34°	077/30°	071/83°	260/07°	170/01°	–	–	–

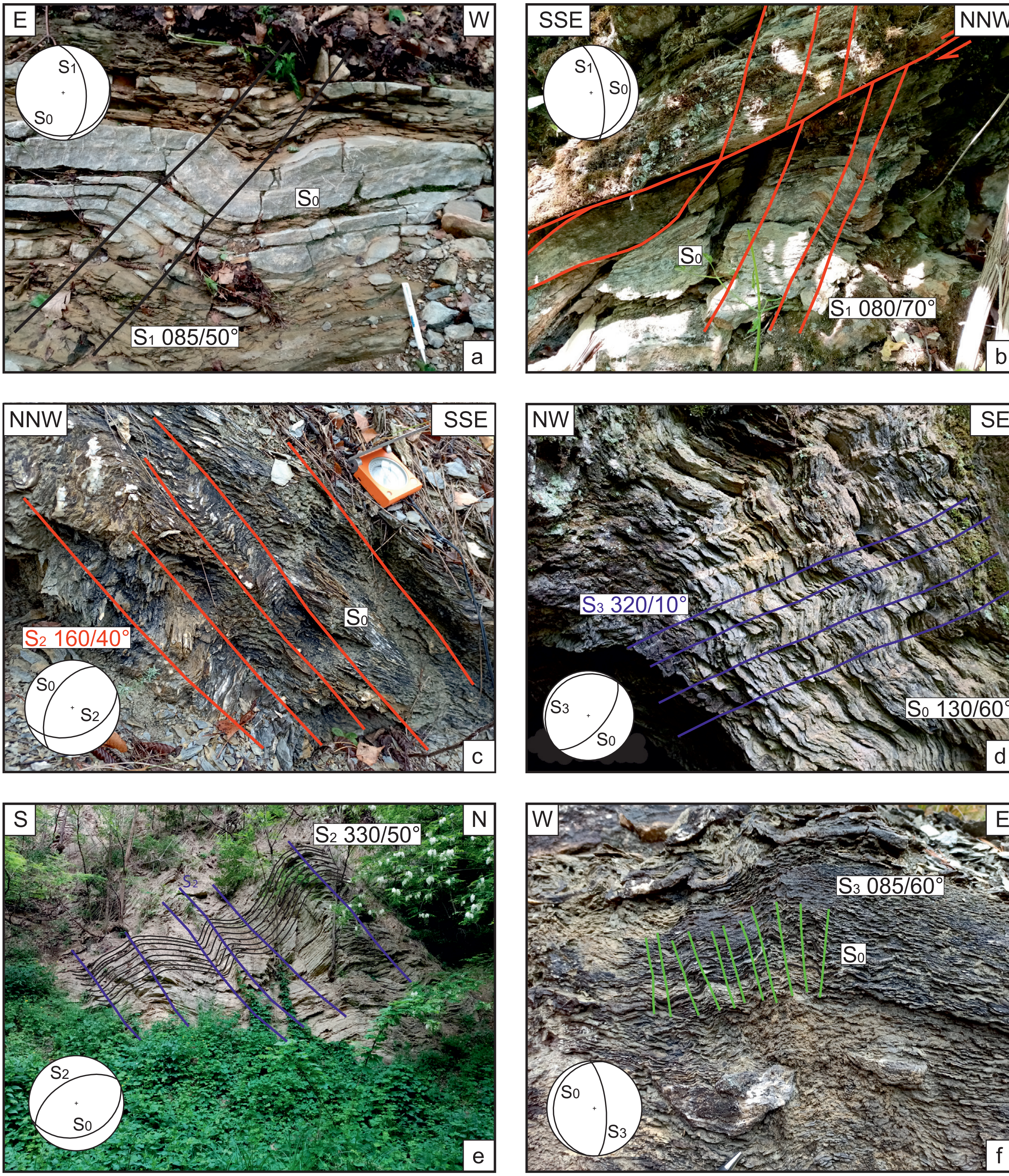

Fig. 4 Macrophotographs of representative structures: **a** – asymmetric fold indicating top-to-the-west thrusting (HCN site); **b** – asymmetric fold indicating top-to-the-west thrusting (LIP site); **c** – well-developed asymmetric kink folds with top-to-the-north-west thrusting (LIP site); **d** – open symmetric harmonic folds with NNE–SSE axial planes (RAR site); **e** – asymmetric fold indicating top-to-the-south-east thrusting (HRU site); **f** – symmetric folding related to F_3 folds.

indicating the E–W shortening. Asymmetric folds have distinct top-to-the-west tectonic transport. The folding is accompanied by spaced fractures and stylolitic cleavages. The fold axes (L_1) have variable N–S plunging, which is caused by reworking and tilting of approximately about 30° on both sides by subsequent deformational phases

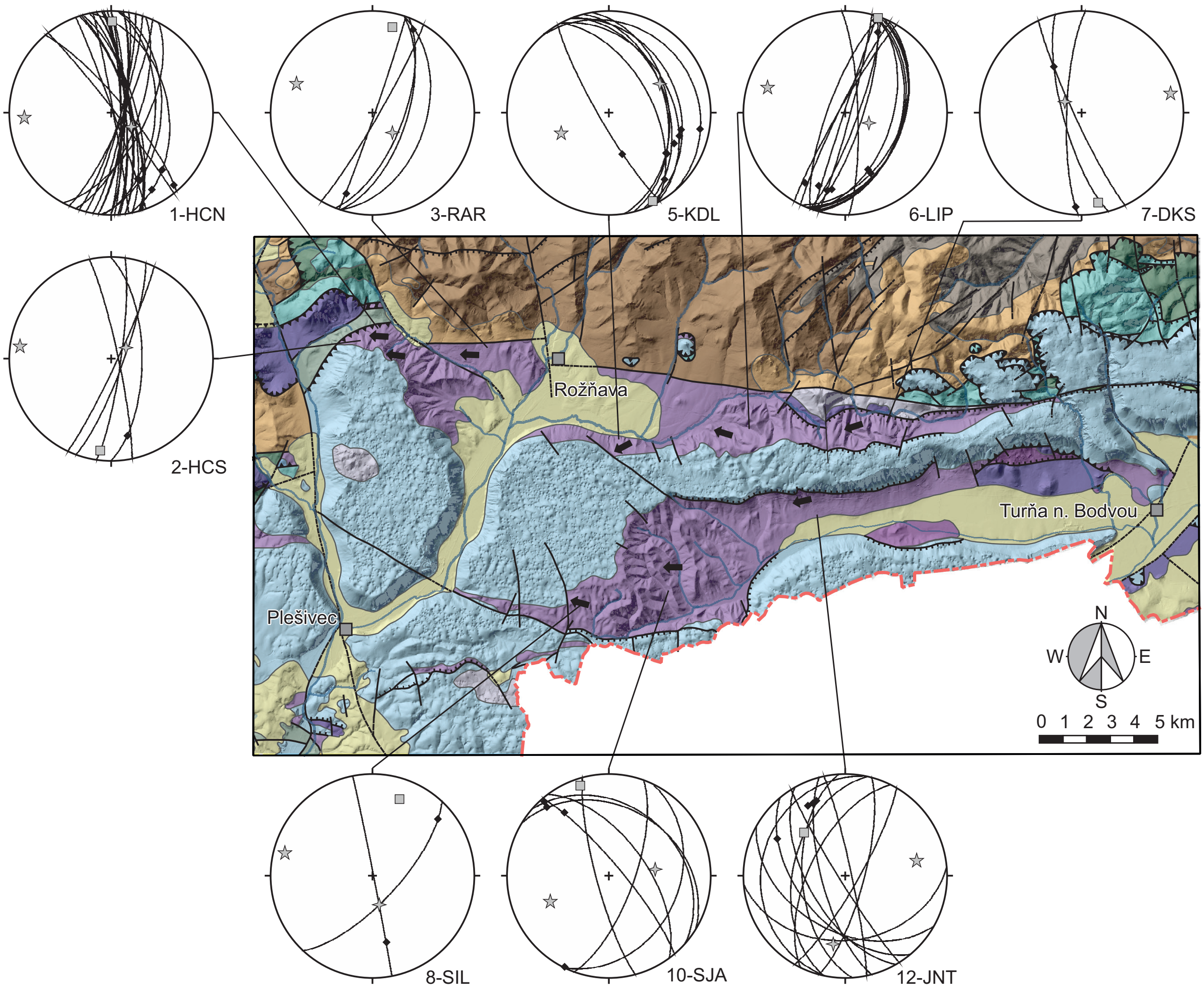

Fig. 5 Tectonic map with black arrows which indicate tectonic transport generally top-to-the-west. Stereograms (Lambert projection, lower hemisphere) represent cleavages and fold axial planes (great circles), fold axes (black full diamonds) and grey symbols (five-pointed star – trend and plunge of principal maximal strain axis [constriction], square – trend and plunge of intermediate strain axis, and four-pointed star – trend and plunge of principal maximal strain axis [elongation]). Measurements were carried out in Lower Triassic sandstones, shales, marlstones, and occasionally well-bedded carbonates (Alpine deformation – AD_1, Late Jurassic to earliest Early Cretaceous).

(Fig. 5 – HCN, HCS, RAR, KDL, LIP, SJA). The folds (F_1) and related deformational structures are occurring predominantly in the middle portion of the Lower Triassic siliciclastic deposits of the Silicic Unit (cf. Fig. 6). In the southern part of the area (Fig. 5 – SIL, JNT, LIP), the folds are practically symmetric with no observable vergence. The size of the folds is variable but generally, the folds' amplitude is from meter-scale to tens of meter-scale, frequently with non-cylindrical hinges.

The second group of structures comprise folds (F_2) with mainly steeply to moderately south-dipping axial planes (S_2) of open to closed folds (Fig. 7). However, upright to steeply northward-dipping fold axial surfaces can also occur. Based on the spatial geometry, it is assumed that these folds form a fan-like shape. Statistically, the northern and central part of the Silicic nappe body has southward dipping of fold axial planes, but the southern part is represented by northward dipping of fold axial planes (cf. Fig. 6 – block diagram).

Besides that, the folds (F_2) have subhorizontal to gently plunging and ENE–WSW trending fold axes (L_2). They are generally symmetric and cylindrical. Some of them are asymmetric with NNW to NW vergence and show maximum shortening in the NNW–SSE, and NW–SE direction, respectively (Fig. 7). Such asymmetric folds have south-eastwards dip direction steep to moderately inclined axial surfaces. The axial surfaces (S_2) coincide also with weakly developed spaced fracture cleavage and occasional solution cleavage in carbonates and marlstones. The fold axial surfaces (S_2) are parallel with observed cleavages (S_2). In the northern part of the study area, kink folds are also frequent and are linked

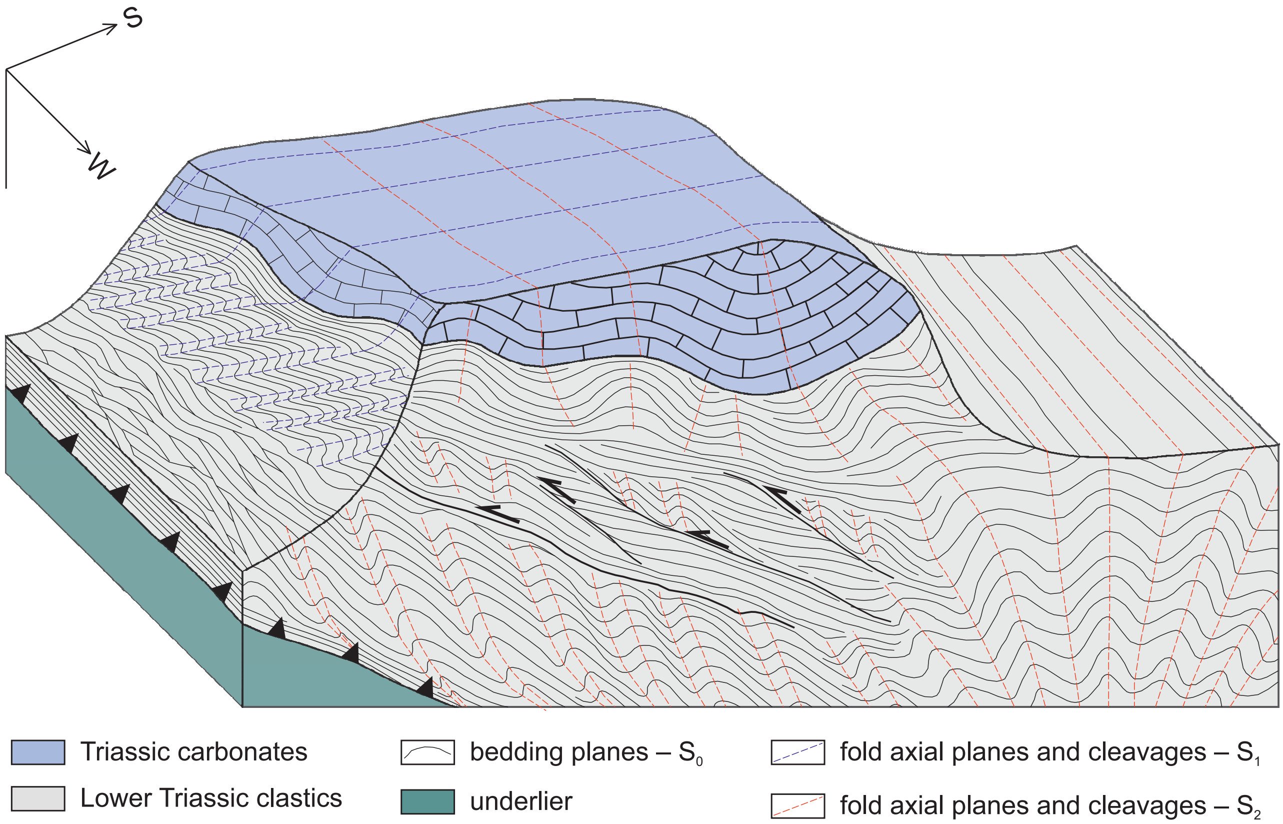

Fig. 6 Simplified idealised model of deformational structures and their spatial distribution in the Lower Triassic mainly siliciclastic deposits of the Silicic Unit.

predominantly to northward movement. The strikes of axial surfaces (S_2) of folds are in W–E direction with the southwards dipping. On the other hand, some folds (F_2) have also a weak southwards asymmetry (Fig. 7).

All these aforementioned F_1 and F_2 fold structures are refolded by harmonic symmetric gentle to open folds (F_3) with N–S trending subhorizontal fold axes (L_3). This group of folds (F_3), which are not affected by tilting and plunging of fold hinges (L_3) is certainly the youngest. The folds can be characterised as upright, cylindrical and harmonic practically with no indication of mass transport (Fig. 8). The fold system refers to initial pure shear shortening in the W–E direction, which at some places indicates the simple shear with eastward fold vergence (Fig. 9 – RAR, KRU, MMA). The AD_3 structures are certainly younger than the AD_2 structural association. Modification of AD_2 structures by the AD_3 phase is also indicated by a girdle of L_2 fold axes, interpreted as their plunge undulation due to superimposed F_3 macroscopic folding.

Towards the overlying Gutenstein Limestone the bedding S_0 continuously changes their attitude from N–S to W–E strikes, however without any visible folding. Besides this, eleven carbonate veins with banded ankerite and siderite or their impregnations were observed. The veins are steeply inclined to subvertical with the strike in both N–S and W–E orientation. The important fact is that the ore veins coincide with the S_1 and S_2 axial surfaces, especially in the antiformal parts of folds. Moreover, the four calcite veins with ankerite and siderite with a thickness from 3 to 10 cm have also been observed in the southern part of the Silická planina Plateau (SIL sector). The strikes of three veins are in the NW–SE direction and are parallel with axial surfaces of folds and the veins were placed to axial surfaces. The last subvertical vein has an N–S strike and crosscuts the older structure.

5. Interpretation of structures and chronology

In this contribution, a large data set of planar (related to bedding) and linear (flute casts) primary structures and deformation structures were documented in the Lower Triassic sediments of the Silicic Unit. Based on the structural analysis, a heterogeneous group of measured structures was identified (Figs. 5, 7, 9; Tab. 1). Geometry and overprinting criteria of secondary planar structures (cleavages, resp. fracture cleavages or fold axial surfaces) and hinge lines or fold axes indicate the presence of three main deformation phases. Two older are associated with deformation structures characterised as pervasive and

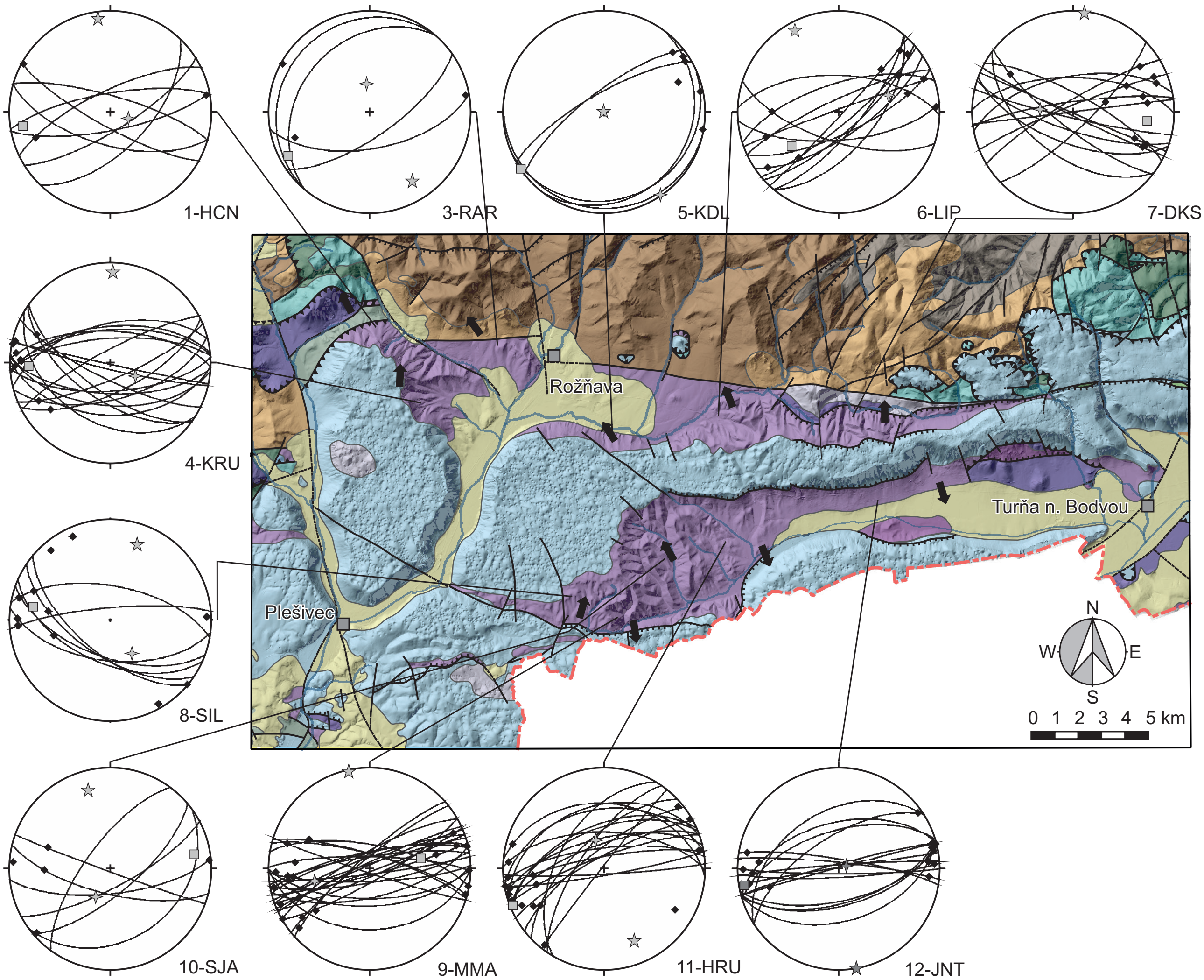

Fig. 7 Tectonic map with black arrows which indicate tectonic transport generally top-to-the-NNW. Stereograms (Lambert projection, lower hemisphere) represent cleavages (great circles), fold axes (black full diamonds) and grey symbols (five-pointed star – trend and plunge of principal maximal strain axis [constriction], square – trend and plunge of intermediate strain axis, and four-pointed star – trend and plunge of principal maximal strain axis [elongation]). Measurements were carried out in Lower Triassic sandstones, shales, marlstones, and occasionally well-bedded carbonates (Alpine deformation – AD_2, mid- to Late Cretaceous).

occurring in nearly the entire sheet of the Lower Triassic sedimentary formations of the Silicic nappe in the Slovak Karst, while the last represents a less intense deformation.

As mentioned hereinbefore, the structural analysis divided the structures into two unambiguous, geometrically different groups. Roughly, the first group of structures is related to ≈W–E shortening and the second one to NNW–SSE shortening. However, when we take a closer look at the symmetry of the structures and their dispersion, we find that both deformation groups can consist of three independent groups. The structures that formed during the approximately W–E shortening can be roughly divided into (1) the asymmetric folds with in most cases top-to-the-west transport (vergence), but not necessarily (Fig. 4a) and (2) the symmetric gentle to open fold with no a direction relating to the sense (vergence) locally with few pronounced asymmetries with top-to-the-east transport (Fig. 4b). Based on the crosscutting/overprinting criteria it is possible to consider the asymmetric structures with westward vergence are the older observed structures.

The structures originated during the generally N–S shortening can be characterised by commonly asymmetric folds with mostly top-to-the-north vergence (Fig. 4c), symmetric folds (Fig. 4d) and locally obscure asymmetries with top-to-the-south transport (Fig. 4e). From field observations, it is possible to define the chronology of these three deformation stages, where the first group of deformation structures is clearly older than the second etc.

The question is what the relationship between the W–E and the N–S shortening is. The answer is neither simple nor unambiguous, which is due to the different intensity of strain in the rocks related to individual deformational phases and to the relatively larger variance of deformation structures. Spatial data variance of tectonic structures depends on their age, what was important knowledge from field observations.

If we fully accept only geometric criteria two deformation phases were identified (W–E and N–S shortenings), then in the observed localities the W–E shortening was in most cases younger (Fig. 4f). However, not exclusively, because in several localities it was possible to observe older structures formed during the W–E lateral shortening, which were overprinted by the N–S shortening. The F_1 folds are refolded and overturned at sites where both structures are present. Therefore, these field observations reflect three phases of deformation.

Based on these arguments, the deformation phases can be arranged as follows in chronological order: (1) The oldest phase (AD_1) is the W–E shortening with the evolution of asymmetric folds (F_1) with in most cases top-to-the-west vergence, (2) The second one (AD_2) is the N–S shortening, which generated commonly asymmetric folds (F_2) with top-to-the-north vergence, but symmetric folds locally obscure asymmetries with top-to-the-south vergence forming a fan of fold axial planes in the southern part of the study area, (3) The last one (AD_3) is the W–E shortening with the symmetric gentle to open fold (F_3) locally with few pronounced top-to-the-east asymmetries.

Moreover, in several sectors of the studied area, it has been observed that the intensity of strain gradually decreases from the base of the nappe towards the middle part of the Lower Triassic formations (Fig. 6). Here the strain again increases approximately up to the base of the Middle Triassic carbonate formation. The variations in the strain intensity are apparently related to the mechanical resistance of studied rocks. This heterogeneity of strain in sedimentary rocks was observed mainly in well-preserved geological profiles especially in the sectors located in the northern rim of the Silicic Unit.

6. Tectonic evolution – a discussion

The inner zones of the Western Carpathians are composed of low-grade Palaeozoic and low-grade to unmetamorphosed Mesozoic complexes showing complicated palaeogeographic affinities to the Austroalpine, South Alpine, and Dinaric facies belts (e.g., Plašienka 2018). The main tectonic deformation of these units took place during the Late Jurassic and Early Cretaceous with predominantly top-to-the-north vergence of principal thrust structures.

The uppermost structure of the Palaeoalpine stack is composed of the Silicic Unit, which consists of internally less complicated nappe bodies detached along the horizon of the Upper Permian–Lower Triassic evaporites and siliciclastic deposits. However, following the first-order nappe stacking, the complex and polygenetic tectonic evolution is also evidenced by slices of ophiolitic rocks of the Meliata Unit incorporated into the evaporite melange in the base of the Silica Unit. Moreover, in many places, the Silicic nappe is lying on various tectonic units with significant structural, metamorphic, and angular discordances. These observations point to the polystage tectonic evolution preserved within the Silicic Unit. The overall structural evolution of the Silicic nappe system revealed three distinct deformation stages AD_1, AD_2, and AD_3 which brings new exact and partly different information on the deformation and tectonic evolution of the study area.

The first group of lateral shortening (AD_1) has been observed on several localities, where the Lower Triassic predominantly siliciclastic rock to marlstones were affected by east-dipping axial fold surfaces and fracture cleavages indicating top-to-the-west thrusting (Fig. 5). This deformation stage is newly defined based on a detailed structural analysis and overprinting criteria. Time and relation of this thrusting phase are interpreted as a continual process following the exhumation of the high-pressure rocks of the underlying Bôrka Nappe revealed by available age data on muscovite from blueschists

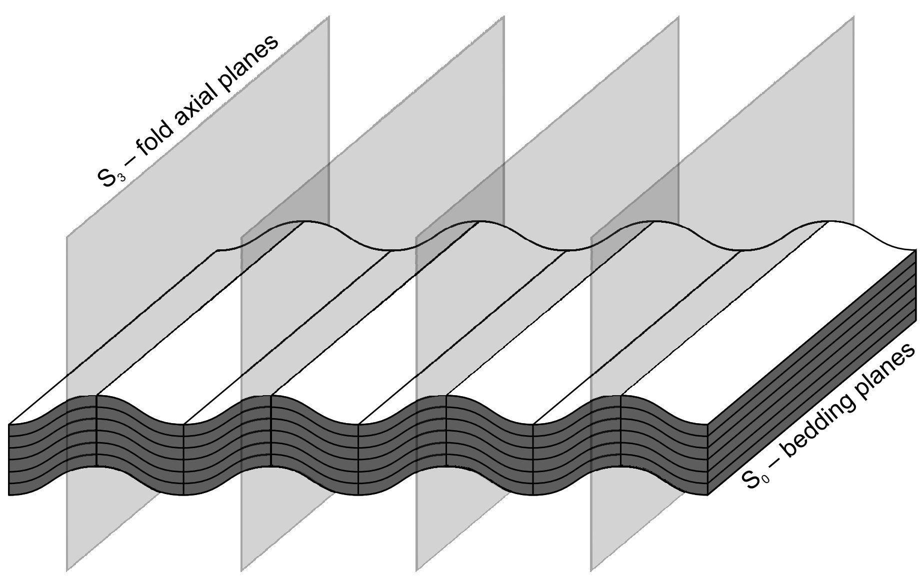

Fig. 8 Model of AD_3 deformational phase with the evolution of simple open symmetric folds with horizontal to gently plunging hinge lines and upright axial fold planes. Such geometry is typical for the folds F_3 related to the third Alpine deformation stage (AD_3).

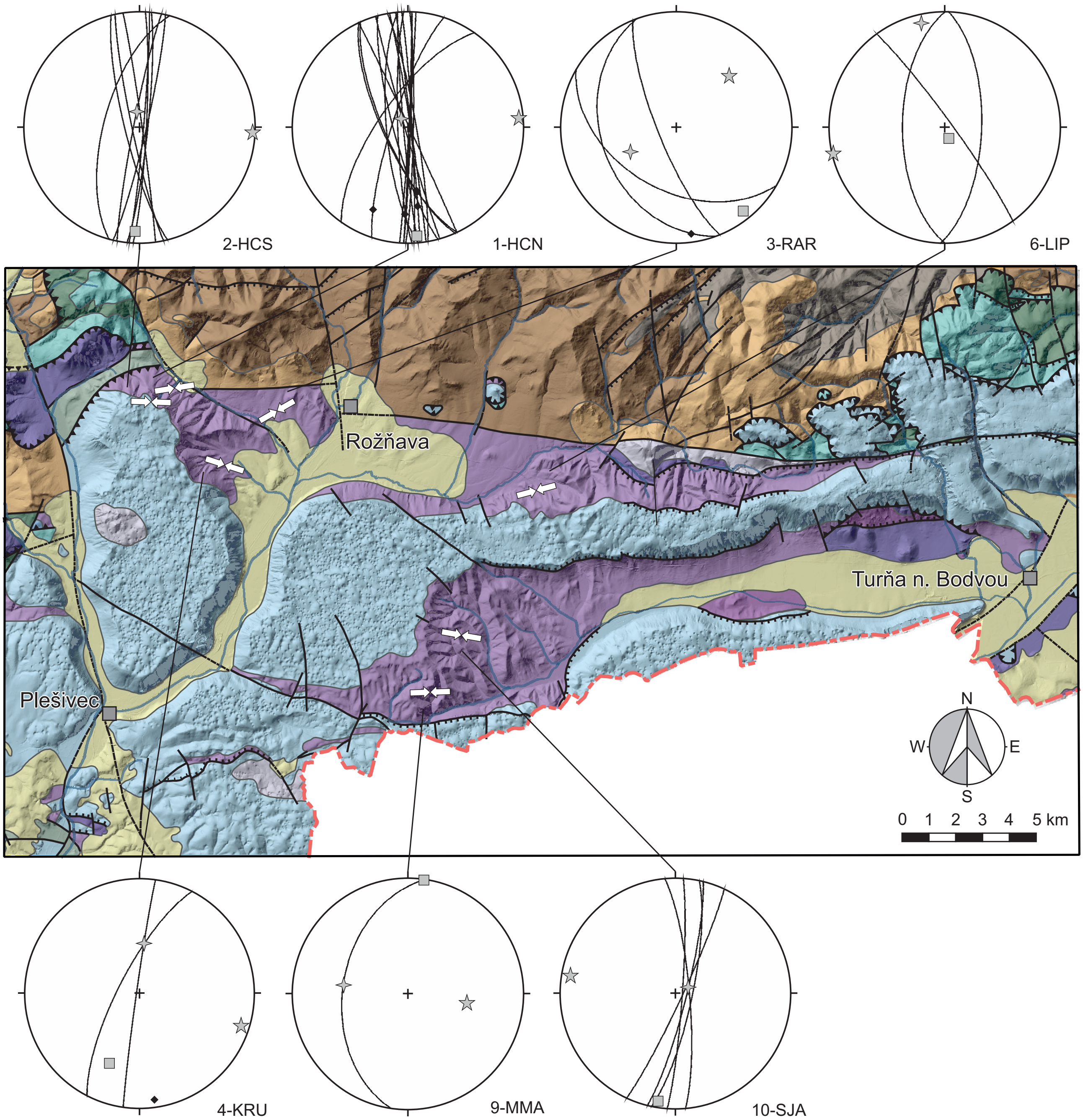

Fig. 9 Tectonic map with white arrows that represent maximum shortening. Stereograms (Lambert projection, lower hemisphere) represent cleavages (great circles), fold axes (black full diamonds) and grey symbols (five-pointed star – trend and plunge of principal maximal strain axis [constriction], square – trend and plunge of intermediate strain axis, and four-pointed star – trend and plunge of principal maximal strain axis [elongation]). Measurements were carried out in Lower Triassic sandstones, shales, marlstones, and occasionally well-bedded carbonates (Alpine deformation – AD_3, tenuously dated back to the latest Late Cretaceous–Early Eocene).

(Maluski et al. 1993; Dallmeyer et al. 1996; Faryad and Henjes-Kunst 1997b; Putiš et al. 2022). We propose that the AD_1 structures observed in the Silicic Unit were formed in the Late Jurassic (~ 167–145 Ma) concerning the subduction of oceanic crusts and closure of the Meliata (Neotethys) Ocean during the Late Jurassic (Maluski et al. 1993; Faryad and Henjes-Kunst 1997a, b; Árkai et al. 2003; Lexa et al. 2003; Vozárová et al. 2008; Putiš et al. 2014) and formation of the Meliata-Turňa-Silica accretionary wedge. During this Late Jurassic to the earliest Early Cretaceous stage, the southeastern margin of the Gemeric Unit collided with the Meliata subduction system. Later, the subduction process was followed by accretion, exhumation of metamorphic units of the wedge and their emplacement onto the Gemeric basement.

It should be noted that practically all the previous studies from the metamorphic units of the Silicic Unit footwall reported only north to northwest tectonic transport of the Silica detachment so far (cf. Hók et al. 1995; Rakús 1996; Dallmeyer et al 2008; Plašienka 2018). However, in the southern part of the Gemeric Unit, sedimentary bedding is well preserved and folded by large-scale open folds with N–S trending hinges (axes). This folding relates to the development of spaced cleavage steeply dipping to the east suggesting that the thinned continental margin was intensively reworked during Jurassic subduction processes (cf. Lexa et al. 2003).

The second group of tectonic structures (AD_2) was determined at many places and is characterised by south-dipping axial fold surfaces and fracture to pressure solution cleavages indicating top to the north thrusting (Fig. 7). The AD_2 is the most prominent deformation in the Silicic Unit. This change in shortening direction is linked with a large-scale and heterogeneous reworking of the whole Meliata accretionary wedge and underlying Gemeric Unit, where a large-scale structure of the Gemer Cleavage Fan was developed during the Early- to mid-Cretaceous. This cleavage fan is a result of an indentation of the Gemeric crystalline basement by a southern crustal block of unknown origin (cf. Lexa et al. 2003). This deformation overprint is related to continent-continent collision during the mid- and early Late Cretaceous ("pre-Gosau" deformation event) and the age of deformation and metamorphism decreases from the hanging wall toward the footwall units in all investigated sections. The thrusting started during Early Cretaceous (137–115 Ma) and is responsible for the nappe stacking of the Veporic and Gemeric crystalline basements incorporated into the orogenic wedge structure of the Central West Carpathians (Plašienka et al. 1997a; Lexa et al. 2003; Dallmeyer et al. 2008; Froitzheim et al. 2008; Vozárová et al. 2008, 2014; Jeřábek et al. 2012; Bukovská et al. 2013; Putiš et al. 2015; Novotná et al. 2015; Plašienka 2018). This tectonic process was also associated with the evolution of lower greenschist facies metamorphism overprint in the southern Gemeric Unit (cf. Hurai et al. 2008, 2015; Králiková et al. 2016). However, in the basement rocks, these ages might reflect the exhumation or equilibration of the isotopic systems during younger deformation processes (Faryad et al. 2020). Towards the south, the folds with north-dipping axial surfaces and occasionally with flat-lying fold axes and backward instabilities concerning the orogen polarity were observed in the Silicic Unit (Figs. 6, 7). Most likely, this structure can be interpreted as a fold fan structure of the Silicic nappe pile.

The AD_2 deformation stage is identical to that of the Tornaic (Martonyi), Aggtelek and Bódva units in the Rudabánya Mts. (Fodor and Koroknai 2000; Kövér et al. 2009) and in the main aspects with that of the Meliatic units (cf. Mock et al. 1998; Mello et al. 1998; Faryad 1999; Dallmeyer et al. 2008). However, in the southern zones, the polarity of tectonic transport is the opposite. In addition, it should be noted that the deformation dominates the present broad-scale structure and was known long ago in the past (e.g., Reichwalder 1982; Hók et al. 1995; Rakús 1996).

Cretaceous tectonics of the Western Carpathians is interpreted by NNW vergent collision of a southern continent with the northerly lying Western Carpathian terrain (European Plate). Lithospheric fragments of the southern continental domain are so far unknown. However, some microfragments located in northern Hungary (Bükk mountains, NE part of Hungary beneath the Cenozoic deposits), are considered to be a part of the southern (Adria) derived continent of Neo-Proterozoic age (e.g., Pantó et al. 1967). The absence of Variscan overprint is manifested by continuous sedimentation from the Early to Late Palaeozoic. We suggest that this southern continent behaved as a rigid indenter controlling the deformation of all northerly foreland crustal units, and in our coordinate system was actively moving towards the north (cf. Lexa et al. 2003).

On the other side, the underlying Gemer Unit was considered to be the weakest domain accommodating most of the viscous deformation during the Cretaceous stage with the evolution of the cleavage patterns in deformable weak rocks which reflect the geometry and direction of movement of rigid blocks (cf. Snopko, 1967; Lexa et al. 2003). Geometrically the same orientation of fold axial planes of AD_2 stage was observed in the Silicic Unit (Fig. 7). Alpine metamorphism of the Gemeric Unit is related to the Jurassic subduction and subsequent collision processes that continued up to the Late Cretaceous. The Gemeric basement with its cover sequences acted as a passive margin of the closed Meliata oceanic basin (Faryad et al. 2005, 2020), which is in line with field relations, observed deformation structures and pressure dominated metamorphic gradient of this overprinting event both in the Silicic and Gemeric units.

A significant reorganisation of the palaeostress field occurred during Palaeocene (AD_3). The principal shortening axis changed its position from the N–S to W–E direction. It is worth noting that the same orientation of the palaeostress field with the general E–W principal horizontal compression axis was also recorded in the Mesozoic to Lower Eocene sediments. The palaeostress field orientation was documented in many places in the Central Western Carpathians (Lexa et al. 2003; Sůkalová et al. 2012; Gerátová et al. 2022). This statement is supported by numerous fault-slip measurements in the latest Eocene and Oligocene sediments where no significant

W–E trending shortening has ever been documented (cf. Marko et al. 1995; Pešková et al. 2009; Vojtko et al. 2010; Sůkalová et al. 2012; Gerátová et al. 2022). This shortening had to be completed at the latest before the transgression of Upper Eocene deposits and for this reason, we suggest the W–E shortening in pure shear-dominated regime associated with the evolution of symmetric folds and N–S striking spaced foliation took place before Upper Eocene.

The Silicic Unit was affected by steep N–S trending cleavage and kink bands (Figs. 8, 9), which reworked the bedding and older planar structures of the Lower Triassic clastic sediments. These kink-bands have steep axial planes and south plunging hinges suggesting the E–W oriented compression. The structures of this deformation stage were also observed in the Meliatic and Turnaic units. For example, a set of kink band folds was observed in the Lower Triassic strata of the Turnaic Unit in the western part of the study area (e.g., Lačný et al. 2016). A similar attitude of fold geometry was also reported from the Hungarian territory (e.g., Fodor and Koroknai 2000; Hips 2001).

7. Conclusion

The Central Western Carpathians has an imbricated structure, which was formed during the Mesozoic era, mainly during the Late Jurassic and Cretaceous period. The Silicic Unit, nappe respectively, is the highest known nappe system in the Central Western Carpathians and it occurs mainly in eastern Slovakia and northern Hungary. The Silicic nappe system is lying on top of the Meliata-Turňa accretionary wedge and/or Variscan consolidated Gemeric and the Veporic crystalline basements.

Based on the structural analysis, geometry, overprinting criteria and metamorphic condition of secondary planar structures (cleavages, resp. joint cleavages or fold axial surfaces) and hinge lines or fold axes indicate the presence of three main deformation events. Roughly, the first group (AD_1) of structures is related to $\approx$E–W shortening, which is interpreted as a sign of the subduction of oceanic crust during the Late Jurassic closing of the Meliata Ocean and indicates top-to-the-west tectonic transport. The younger direction of thrusting (AD_2) of the Silicic nappe system is top-to-the-NNW simple shearing and is related to the Early Cretaceous tectonics and evolution of fan-like cleavage. The last observed structures (AD_3) refer to the E–W shortening with the symmetric gentle to open fold with subvertical axial surfaces locally with few pronounced top-to-the-east asymmetries.

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