Special Session S09
Geology of the Pieniny Klippen Belt and the role of zones with extensive shortening in the structure of orogenic belts

Scientific Annals, School of Geology, Aristotle University of Thessaloniki Proceedings of the XIX CBGA Congress, Thessaloniki, Greece	Special volume 100	197-207	Thessaloniki 2010

GEOLOGY AND TECTONICS OF THE VRŠATEC KLIPPEN AREA (PIENINY KLIPPEN BELT, WESTERN SLOVAKIA)

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Abstract: The Pieniny Klippen Belt (PKB) is a narrow (merely several km), but lengthy (up to 600 km) zone dominated by Late Oligocene – Miocene wrench tectonics. It separates the Cenozoic accretionary complex of the External Western Carpathians from the Cretaceous nappe system of the Central Western Carpathians. Our investigation was focused on the tectonic structure and evolution of the Vršatec klippen area in the western Púchov sector of the PKB. The studied area includes the Oravic (Czorsztyn, Kysuca, Orava and Transitional Units) and the "non-Oravic" tectonic units (Klape and Drietoma Units). Detailed geological mapping and systematic field structural research of meso-scale deformational structures revealed the record of multistage tectonic evolution during the Senonian – Pliocene times. The oldest recognized stage resulted in formation of the Mesoalpine fold-nappe system of the PKB due to subduction and closure of the Vahic Ocean during the Senonian – Early Eocene times. This compressive stage was accompanied by thrusting of the presently most external Kysuca Unit over the Czorsztyn and transitional units and by formation of macroscopic folds with the NNE-SSW to NE-SW trending fold axes. The main compression was oriented perpendicularly to the strike of the PKB recently trending in the SW-NE direction. The thrusting and folding were followed by several brittle deformation stages. The oldest stages (E-W to NW-SE oriented maximum compression) produced the NE-SW trending dextral positive flower structure along the western boundary of the PKB and resulted in the final morphostructural character of klippen with long axes oriented in the NE-SW direction. The dextral transpression was a result of the continuing shortening and relative counterclockwise rotation of the ALCAPA block in the Late Oligocene – Early Miocene. The younger N-S oriented compression (Early – Middle Miocene) produced mainly sinistral faults roughly parallel to the strike of the belt in the sinistral transpression regime. The apparent shift of the main compression to the N-S direction was an effect of a rigid counterclockwise rotation of the ALCAPA block during the Early Miocene. Mostly strike-slip and normal faults were formed during the next two tectonic events (Middle to Late Miocene) as a product of the transtensive tectonic regime with NNE-SSW to NE-SW trending compression. Active clockwise rotation of the main compressional stress axis from N-S to NE-SW direction, and inversion from the older transpression to the younger sinistral transtension resulted from NE-ward translation of the ALCAPA block. The NE-SW trending normal faults were generated by the NW-SE extension during the final deformational phase under the extensional tectonic regime (Pontian – Pliocene).

Keywords: Western Carpathians, Pieniny Klippen Belt, Vršatec klippen area, Mesozoic successions, tectonic structure, palaeostress analysis.

1. Introduction

The Pieniny Klippen Belt (PKB) represents a tectonic zone connecting the Cenozoic accretionary wedge of the External (Outer) and the Cretaceous nappe system of the Central (Inner) Western Carpathians (Fig. 1). It is an internally complicated narrow structural belt, which stretches in a broad arc for about six hundred kilometres from the Alpine-Carpathian junction area as far as northern Romania. Regardless of its length and intricate internal structure, the PKB preserves its tectonic integrity, indicated especially by the omnipresence of its typical Oravic units that do not occur in other Carpathian zones. In addition, certain parts of the PKB involve also the "non-Oravic" units of the Central Western Carpathian (CWC) provenance which were incorporated into the PKB and attained its tectonic style after their nappe emplacement during mid-Cretaceous times. These are the Klape, Drietoma and Manín Units in western and the Haligovce Unit in eastern Slovakia. Their palaeogeographic and tectonic affiliation was interpreted in various ways, most probably all these units represent frontal nappe elements of the Fatric (Krížna) nappe system (see e.g. Plašienka, 1995; Froitzheim et al., 2008 and references therein).

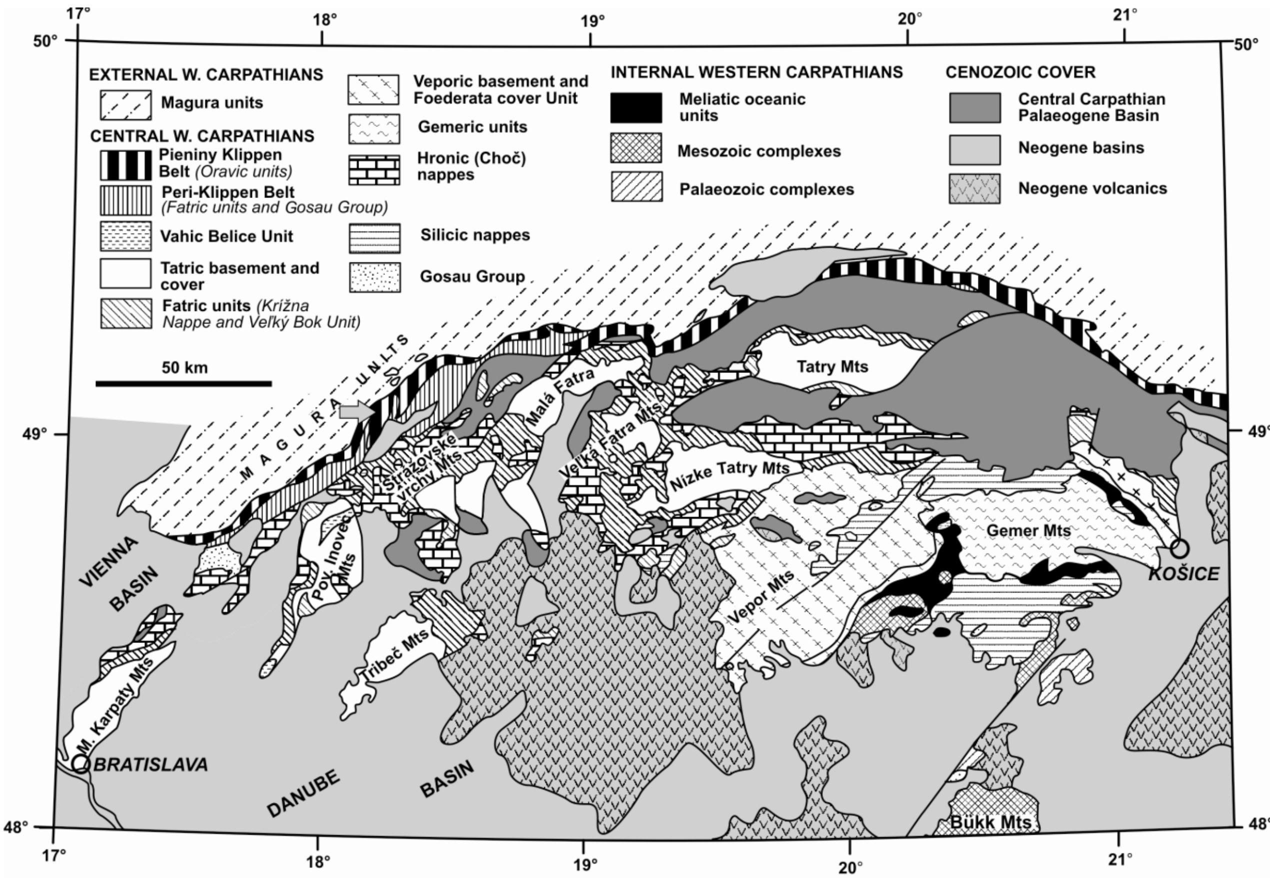

Fig. 1. Simplified tectonic map of the Central Western Carpathians. All boundaries of pre-Cenozoic units are tectonic in origin. Grey arrow in the left part of the figure shows location of the studied area (modified after Plašienka 1998).

The following features are typical for the Oravic units: absence of pre-Mesosoic rocks, scanty representation of Triassic carbonates, variable developments of Jurassic and Cretaceous successions and rarely preserved complete stratigraphic successions. The surface structure of the PKB shows the “klippen tectonic style”, where mostly tectonically separated klippen (rigid Jurassic – Lower Cretaceous limestone blocks) are embedded in the “klippen mantle” formed by the Lower Jurassic and Upper Cretaceous to Palaeogene marlstone and flysch formations. Limestone olistolites are present in places as well. The mid-Cretaceous and Senonian marly and flysch formations were originally parts of continuous Oravic successions, but due to higher ductility they were detached and intensely tectonized to form the “klippen mantle”.

The complex internal structure of the PKB was caused by several deformational phases, which operated in brittle-ductile and brittle deformational conditions at relatively small depths. Its recent shape was a result of mainly Cenozoic destruction of the Mesoalpine fold-nappe system. According to the present views, the main phase of tectonisation and separation of the klippen took place after the Eocene – Oligocene and before the Sarmatian (Kováč and Hók 1996; Potfaj 1998). According to Ratschbacher et al. (1993) and Nemčok & Nemčok (1994), the resulting deformation style of the PKB was governed by dextral transpression. The presently observed deformation structures are dominantly brittle. Mesoscopic dislocations prevail and form dense networks in all rock complexes. Well-bedded sequences often exhibit fold structures.

Our study concentrates on the structure and tectonic evolution of one of the most conspicuous parts of the PKB – the so-called Vršatské bradlá group of klippen in the Middle Váh river region of western Slovakia (the Púchov segment of the PKB – see Fig. 1 and 2). Taking as a whole, the Vršatec area represents the largest Czorsztyn-type klippe or a group of klippen in the whole PKB.

2. Geological settings

The Púchov sector of the PKB, located between the Vlára river valley and town of Bytča in NW Slovakia, is a NE-SW trending, approximately 45 km long and up to 20 km wide zone of extremely complex structure. It involves all types of tectonic units known in the PKB, including the Oravic Superunit, as well as the "non-Oravic" units of the CWC affiliation (Fig. 2).

Senonian – Palaeogene overstepping cover (Gosau Supergroup), with occasional tectonic windows of Oravic units. This zone was designated as the "Periklippen Zone" by Maheľ (1980).

The "non-Oravic" Periklippen zone is composed by three large units. The Drietoma Unit, embracing the Upper Triassic – Cenomanian, dominantly basinal succession of likely Fatric (Krížna – Zliechov Succession) provenance, overrides the Oravic

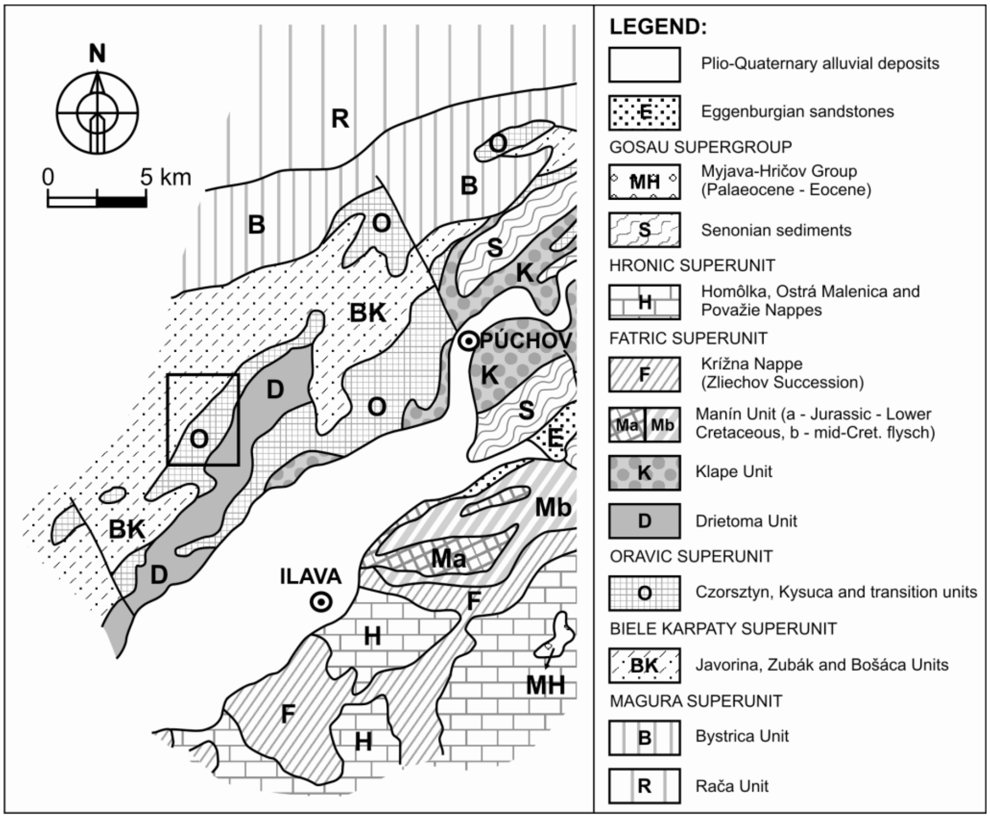

Fig. 2. Distribution of the principal units in the broad vicinity of the Vršatec klippen area. Rectangle in the left part of the figure shows location of the studied area (modified after Schlögl et al. 2008).

The Oravic Superunit includes typical klippen of the ridge-derived Czorsztyn Succession, the basinal Kysuca Succession (corresponding to the Polish Branisko Succession) and several types of "transitional" successions as the Pruské Succession (corresponding to the Niedzica Succession from the Polish part of the PKB – cf. Aubrecht and Ožvoldová 1994), the Orava Succession (Schlögl et al., 2000), the Mariková Succession (Plašienka et al., in press), or the Streženice Succession (Began and Borza, 1963). Klippen of the Oravic Superunit occur along the northwestern margin of the PKB, forming a narrow "Klippen Belt *sensu stricto*". The much broader southeastern part is mostly built by the "non-Oravic" units and their

units. It forms synclinal tectonic outliers in the Vršatec area, but dominates towards the SW in the Trenčín sector of the PKB. The youngest member of the Drietoma Unit is the mid-Cretaceous (Albian – Cenomanian) synorogenic flysch with "exotic" conglomerates. This provides a link to the huge Klape Unit, which prevails in the Púchov Periklippen Zone. The Klape Unit is composed of some thousand metres thick mid-Cretaceous wildflysch complex (the Klape Flysch) with big olistolites of Triassic and Jurassic carbonates (e.g. the spectacular Klape Klippe; see Marschalko, 1986).

The SE-most component of the Periklippen Belt is the Manín Unit. Its Lower Jurassic – Cenomanian sequence (including the characteristic Urgon-type platform limestones) closely relates to the Vysoká-type ridge successions of the Fatric Superunit (e.g. the Belá Unit in the adjacent Strážovské vrchy Mts – Maheľ, 1978). However, many authors prefer the Tatric affiliation of the Manín Unit (e.g. Rakús and Hók, 2005). The Manín Unit is dominated by mid-Cretaceous hemipelagic and flysch formations, older solid limestones build several large "klippen" which are in fact brachyanticlines. Senonian sediments within both the Klape and Manín Units were either considered to be their integral continuous sequences (Salaj, 1990), separated by a stratigraphic hiatus in places (Marschalko and Kysela, 1980), or tectonic windows of the underlying Kysuca Unit (Podháj Succession – Rakús and Hók 2005). The mid-Cretaceous flysch of the Manín Unit is from the SE overridden by the frontal Fatric elements with the basinal Zliechov Succession (typical Krížna Nappe).

In places along the NW margin of the Púchov sector of the PKB (Vršatec, Mariková), it can be documented that the Oravic units overthrust various Upper Cretaceous – Eocene flysch formations of the Magura and/or Biele Karpaty Superunits of the External Carpathians. However, this early (probably Eocene) thrust-related structure was strongly overprinted by the Miocene transpression; consequently all units are forming a broad positive flower structure. Oravic units along the NW margin are mostly steeply SE dipping, while the Periklippen Belt is affected by large-scale upright folding. Local axial plane cleavage is developed in the fold hinges. Macrofold axes strike parallel, or slightly oblique to the belt boundaries. They are seldom horizontal, but rather plunging in both directions, thus forming brachyclines. Numerous post-folding faults – slickensides are generally steep to vertical, with gently plunging striae pointing to an oblique- or strike-slip kinematics. In the NE tip of the Púchov sector, near the town of Bytča, the PKB is rapidly narrowing, almost disappearing, due to dextral offset along the W-E trending Bytča fault zone. The next Varín sector of the PKB is W-E trending and located within the southern limb of the structural flower, therefore it is strongly affected by backthrusting (Kováč and Hók, 1996; Marko et al., 2005).

The structural relationships in the Púchov sector of the PKB indicate the emplacement of the Fatric "Periklippen" nappes was the first tectonic event (e.g. Plašienka and Jurewicz, 2006). However, this can hardly be documented by the mesostructural record. This event was followed by the downward (NW-ward) propagated, piggy-back mode of thrusting of Oravic units during the Late Cretaceous – Early Cenozoic succeeded by large-scale upright folding. Shortening passed into dextral wrenching during the Oligocene – Lower Miocene, which incorporated also the Eggenburgian (Burdigalian) sediments in places. The Middle – Late Miocene period is characterized by sinistral transtension along the Mur – Mürz – Leitha – Dobrá Voda – Považie – Žilina wrench corridor, and opening of the small Ilava Basin filled with Pliocene – Quaternary fluviatile sediments (e.g. Kováč, 2000).

The studied terrain of the Vršatec klippen area is formed by two partially independent segments – the Vršatec-Javorník (eastward) and Chmeľová regions (westward) (Fig. 3). The southern, NE-SW trending, Vršatec-Javorník row of picturesque blocky klippen is composed of massive Jurassic – Lower Cretaceous limestones forming a steeply NW-dipping monoclinal slab with overturned stratigraphic sequence belonging to the Czorsztyn Unit. The sequence starts with the Upper Liassic – Aalenian dark hemipelagic marlstones (Krempachy Fm) followed by massive, white bioherm limestones (Vršatec Fm), most probably Lower Bajocian in age (Schlögl et al. 2006). Bioherm limestones are followed by crinoidal limestones (Smolegowa and Krupianka Fms; terminology of lithostratigraphic units mainly according to Birkenmajer 1977), red micritic, locally nodular limestones (Czorsztyn and Bohunice Fms) and whitish to pink biodetrital limestones (Dursztyn Fm). From the SE side, this about 50–150 thick slab of competent limestones is in contact with Upper Cretaceous red pelagic marlstones of the "couches-rouges" type (Púchov Fm). Both Lower Jurassic and Upper Cretaceous marlstones form the so-called "klippen mantle", i.e. a soft matrix in which the stiff klippen are embedded. The lithological contacts, though generally in stratigraphic sequence, are tectonically reactivated in most cases. To the SE, the Púchov marlstones are juxtaposed to various sediments of distinct units participating on the PKB structure (Klape, Orava and Drietoma Units – Schlögl et al., 2000).

In the Chmeľová area, the Oravic Czorsztyn, Kysuca and two transitional successions crop out in a relatively small area, being deformed in a complex fold-fault structure. The Czorsztyn Succession slightly differs from the above-described succession by lack of the bioherm Vršatec limestones. The Kysuca Unit was discerned in the most external position in this region. It involves deep-water pelagic Jurassic strata (predominantly marlstones and radiolarites), but the Lower Cretaceous sediments are of special type with allodapic biodetrital limestones-the Horná Lysá Fm (Mišík et al., 1994).

The first transitional unit is situated in the eastern margin of the Chmeľová region. The unit contains allodapic crinoidal calciturbidites above the Krempachy and Skrzypny Fms (Aalenian – Lower Bajocian), which are analogous to the Samášky Fm described from the transitional Pruské Succession (Aubrecht and Ožvoldová, 1994). There occur also red crinoidal limestones (Krupianka Fm, Upper Bajocian), which are characteristic rather for the Niedzica than for the Pruské Succession. Younger members are represented by red nodular limestones (Niedzica Fm, Upper Bajocian – Callovian) and radiolarites (Czajakowa Fm, Oxfordian).

The second transitional unit is situated at the southeast margin of the Chmeľová region. Its sedimentary succession contains also volcanic rocks and cannot be assigned to any typical Oravic successions described in the literature so far. Dark grey spotty limestones with intercalations of sandy crinoidal limestones and spongiolites represent the oldest members, which are partly analogous to the Bajocian – Bathonian Samášky Fm described from the transitional Pruské Succession (Aubrecht and Ožvoldová, 1994), or to the Bajocian Flaki Fm known from the Branisko (Kysuca) Succession in Poland (Birkenmajer, 1977). These sediments are overlain by greenish and red platy radiolarites (Sokolica and Czajakowa Fms), followed by red nodular limestones (Czorsztyn Fm). Lower Creta-

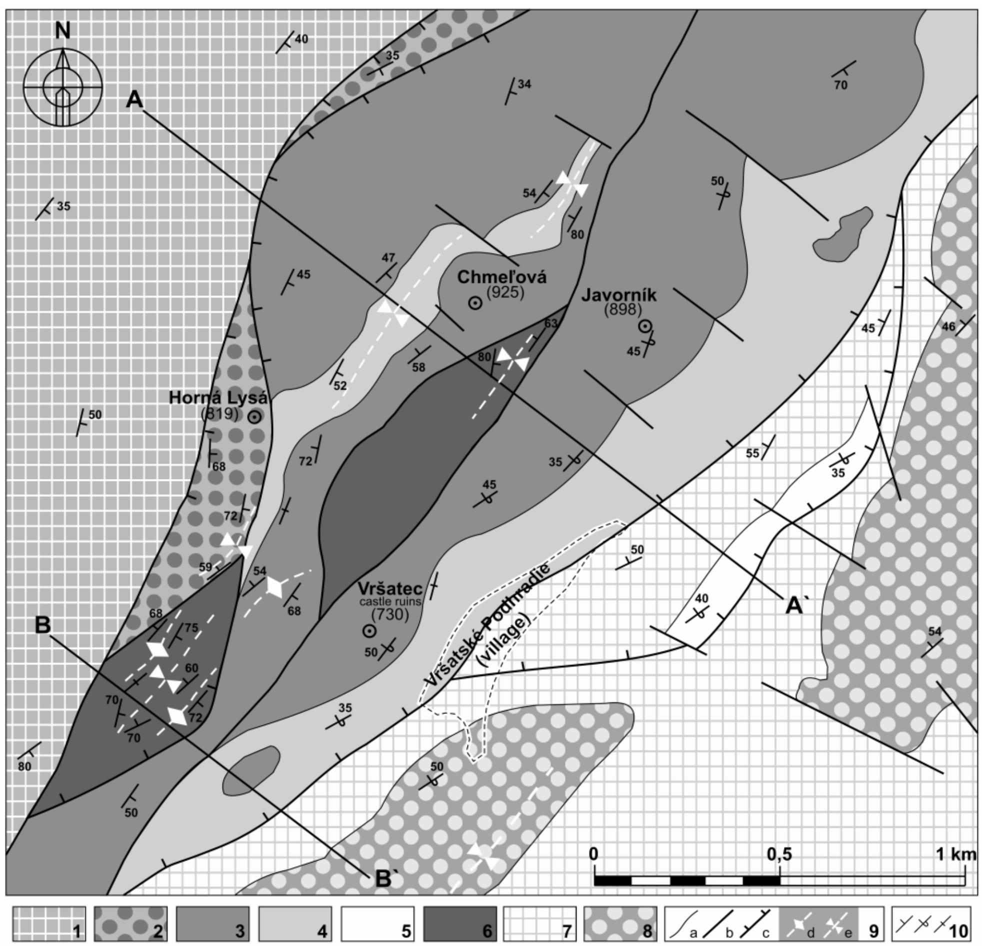

Fig. 3. Simplified tectonic map of the Vršatec klippen area. Carpathian Flysch Belt: 1 – Biele Karpaty Superunit; Pieniny Klippen Belt – Oravic units: 2 – Kysuca Unit; 3 – Czorsztyn Unit: Czorsztyn Sequence (klippes); 4 – Czorsztyn Unit: Púchov-Jarmuta Group ("klippen mantle"); 5 – Orava Unit; 6 – transitional units (undivided); Pieniny Klippen Belt – non-Oravic units: 7 – Klape Unit; 8 – Drietoma Unit; general explanations: 9a – boundaries of tectonic units; 9b – strike-slip faults (undifferentiated); 9c – reverse faults; 9d – anticline axis; 9e – syncline axis; 10 – strike and dip of beds: normal, overturned and upright position.

ceous sediments are represented by pinkish allodapic bioclastic limestones (Horná Lysá Fm – Mišík et al. 1994). Brick-red marlstones, which can be possibly correlated with the Cenomanian Lalinok Fm and the volcanic rocks (alkali basalts of probably Late Cretaceous age – Spišiak et al., 2008) are the youngest components of this succession. The described succession bears features of either a non-typical Kysuca Succession, or the transitional Pruské Succession. Palaeogeographically, both transitional successions most probably occupied a position along a distal slope of the Czorsztyn Ridge at the transition to the Pieniny Basin. To the NW, the Kysuca and the second transitional units are juxtaposed to the flysch sediments of the Biele Karpaty Superunit. Towards the east, these successions are in a tectonic juxtaposition with the typical Czorsztyn Succession of the Vršatec-Javorník region (Fig. 3).

The Maastrichtian – Palaeocene flysch sediments occurring westward of the Oravic units in the Chmeľová area belong to the Biele Karpaty Superunit of the Carpathian Flysch Belt (External Western Carpathians, EWC). The composition and lithostratigraphic succession of this unit is basically different from the other units of the EWC (Potfaj, 1993); the relations to the northern Magura units and to the Klippen Belt are tectonic all along their contacts. Its inner structure has a fold-and-thrust character with NW-vergency, which resulted from formation of the EWC accretionary prism and flysch nappes during subduction of an oceanic crust underlying the EWC flysch basins. The tectonic deformation of the Biele Karpaty nappe group is post-Eocene in age (Potfaj, 1993). The bedding of the flysch sediments neighbouring the Oravic units is generally SE-dipping in normal or reverse position (cf. Mello et al., 2005). This bedding arrangement was primarily a result of the early fold and thrust structure; secondarily it was affected by the Cenozoic transpression. Consequently, the whole Chmeľová area is forming a part of a broad positive flower structure along the strike-slip zone (Fig. 4). The contact with the PKB is most probably followed by a large wrench fault that forms the northern boundary of the PKB.

3. Methods

Our reconstruction of the geological structure and tectonic evolution of the Vršatec klippen area is based on a new detailed geological mapping at the

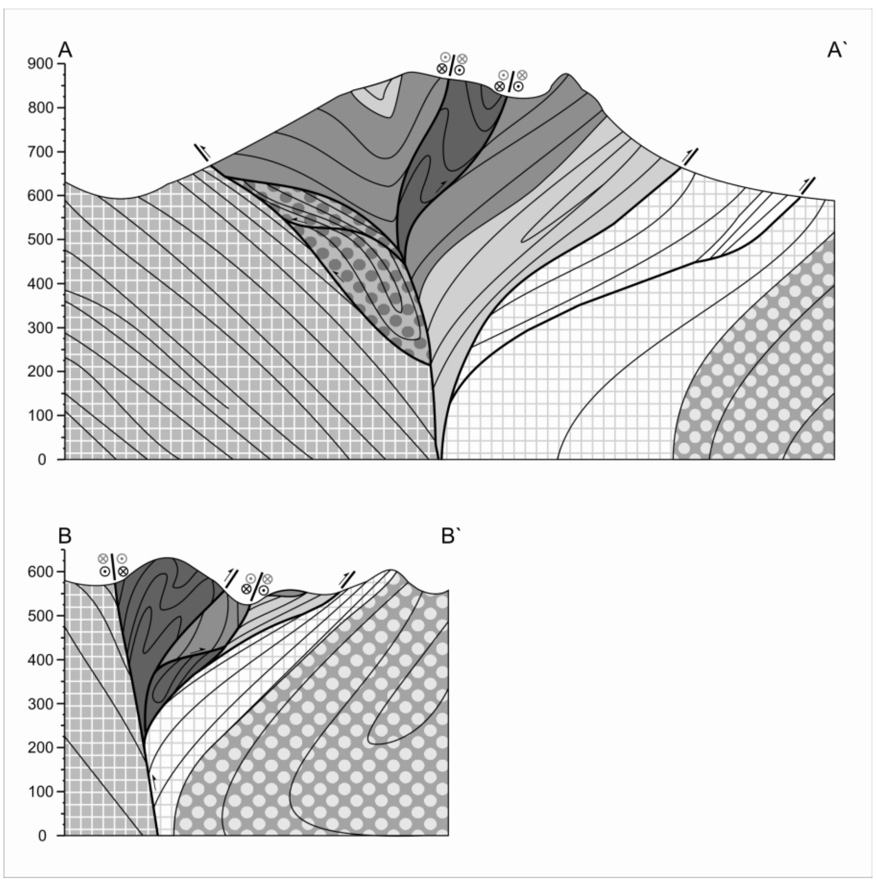

Fig. 4. Cross-section through the Vršatec klippen area. For the location and key see Fig. 3.

scale of 1: 5 000 supplemented by data from the neighbouring areas (Schlögl et al., 2000; Mello et al., 2005). Systematic field structural research of meso-scale deformation elements was focused on fault and fold structures. The analysis of the fault kinematics was based on interpretation of indicators occurring on the slickenside surfaces, along with evaluation of outcrop-scale structures genetically related to faulting. The interactions of the faults observed in the field were used for determination of the relative chronology of the separated homogenous fault groups. The measured slickenside lineations were then processed by analytical palaeostress inversion method (Angelier, 1989; 1994) using the software package Win_Tensor (Delvaux, 1993; Delvaux and Sperner, 2003). The measured bedding and axial plane cleavage attitudes were used for the analysis of fold geometry and orientation. Fold axes are considered to be generally perpendicular to the maximum compression (maximum principal palaeostress axis σ_1). Macroscopic fold axes (β axes) were calculated by the Fabric 7 software (Wallbrecher, 1986).

4. Results

All measured deformational structures were collected from the Oravic units of the Vršatec klippen area. The age range of the investigated rocks is from the Jurassic to the Late Cretaceous. The NW Chmeľová area is internally tectonically complicated, with alternating sectors of normal and reversed stratigraphic sequences. Unlike in the Vršatec-Javorník area to the SE, this region is dominated by macroscopic fold structures (Fig. 3 and 4). Folding was enabled by a much thinner competent limestone layer (ca 10–25 m only) sandwiched between incompetent strata. Folds are mostly upright, slightly asymmetric, with NNE-SSW to NE-SW trending axes and with locally penetrative axial plane cleavage. The cleavage is generally subvertical, but fanwise arranged – steeply northwest dipping in the southwestern sector of the Chmeľová area and mostly steeply southeast dipping in the northwestern sector. The map view and the presence of numerous slickensides postdating the cleavage reveal that folding was followed by brittle deformation that finally shaped the klippen tectonic style of the area.

Meso-scale slickensides were studied in numerous outcrops over the whole studied area. All outcrops exhibit six brittle deformational phases: D1 as the oldest and D6 as the youngest one (Fig. 5; Tab.1). The oldest deformational stage D1 was accompanied by the formation of strike-slip faults (D1a: ENE-WSW trending dextral and NW-SE trending sinistral strike-slip faults) and rarely by NE-SW trending oblique reverse faults with the dextral component (D1b). The horizontal principal compressive stress axis σ_1 was oriented in the E-W direction (in present coordinates). Generally, these faults were activated under the transpressive tectonic regime. NE-SW trending oblique reverse faults indicate the change of the tectonic regime from the pure transpression dominated (E-W oriented σ_1 axis) to the transpressive-compressive regime with the NW-SE horizontal principal compressive stress axis σ_1 (deformational stage D2). Generally NE-SW oriented reverse faults (D2b) were formed; strike-slip faults were still active too (D2a: N-S-trending left-lateral faults and nearly E-W-trending right-lateral faults). Whilst the strike-slip faults are distributed equally throughout the studied area, the reverse faults show different dips in the eastern (only towards the NW), central (both NW and SE-dipping faults) and in the north-westernmost part (mostly SE-dipping) of the area.

The next change of the tectonic regime occurred during the younger N-S oriented compression. Predominantly NNE-SSW trending left-lateral and NW-SE dextral faults (D3a) and rare E-W trending reverse faults (D3b) were formed as the result of the purely transpressive tectonic regime (deformational event D3). On the contrary, mostly strike-slip and normal or oblique normal faults (tensors D4 and D5) were created as the record of the next two strike-slip (transtensive) regimes with NNE-SSW (D4) to NE-SW (D5) oriented σ_1 axis. The last deformation phase D6 is characterized by a number of conjugate normal faults as the result of the extensional tectonic regime with the NW-SE oriented σ_3. Generally, the NE-SW-trending normal faults reactivated the pre-existing weakness zones – either the bedding planes, or older reverse faults. We suppose that normal faulting had already started during the transtensive regimes D4 and D5.

5. Interpretation and Discussion

Summing up, thrusting of the presently most external Kysuca Unit over the Czorsztyn and transitional units was the oldest event recognized in terrain of the Vršatec klippen group. Thrusting was accompanied by formation of macroscopic folds with the NNE-SSW to NE-SW trending fold axes, which are well preserved in the Chmeľová area (Fig. 4). Folding occurred at comparatively greater

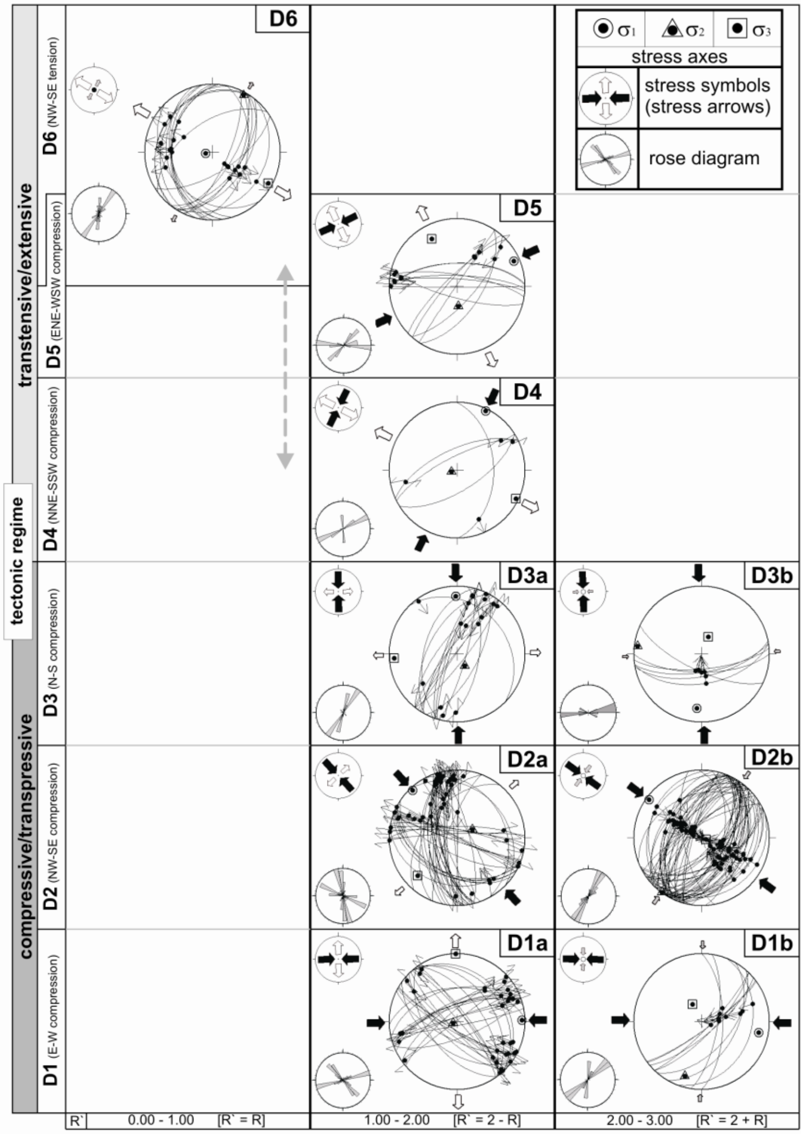

Fig. 5. Synthetic chronological table of all palaeostress tensors from fault slip data (D1a and D1b as the oldest homogenous groups of faults to D6 as the youngest one) and deformational stages (D1 as the oldest to D6 as the youngest one) observed in the Vršatec klippen area. Each homogenous group of faults is represented by stereogram (the fault planes are plotted as great circles with observed slip lines and slip senses using stereographic projection – Schmidt net, lower hemisphere).

depths (but still beyond intracrystalline ductile deformation mechanisms) with development of cleavage formed by pressure solution. The main compression was oriented perpendicularly to the strike of the belt recently oriented in the NW-SE direction. This strong compressive tectonic event resulted in formation of the Mesoalpine fold-nappe system due to subduction and closure of the Vahic Ocean during the Senonian – Early Eocene times (Ratschbacher et al., 1993; Plašienka, 1995). Thrusting and folding were followed by brittle deformation (Fig. 5). The oldest brittle tectonic stages with E-W to NW-SE oriented maximum compression produced mainly reverse, oblique reverse (parallel to the strike of the belt) and strike-slip faults. These meso-scale brittle structures were created under the transpressive to compressive tectonic regime. The distribution of differently dipping NE-SW reverse faults throughout the studied area well documents the NE-SW trending positive flower structure (Fig.4). These tectonic processes were accompanied by the relative counterclockwise rotation of the Central Western Carpathian block with respect to Europe, which generated a

Table 1. Palaeostress tensors from fault slip data. Explanations: Tensor name – name of the homogenous group of faults; n - number of fault-slip data used for stress tensor computation; σ_1, σ_2 and σ_3 - principal stress axes in format azimuth/dip (in degrees); R - stress ratio $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$; R` - tensor type (or stress regime) index as defined in Delvaux et al. (1997); α - mean slip deviation (angle between observed and computed slip directions, in degrees); Q (QRw) – World Stress Map project (WSM) quality ranking as defined in Sperner et al. (2003): A (best) to E (worst).

Tensor name	n	σ_1	σ_2	σ_3	R	R`	α	Q (QRw)	Stress regime according to Delvaux et al., 1997
D6	21	258/82	029/05	119/06	0.3	0.3	6.39	B	pure extensive
D5	12	066/09	176/66	332/22	0.4	1.6	9.67	C	pure strike-slip
D4	4	026/04	252/83	116/04	0.52	1.48	13.9	E	pure strike-slip
D3a	16	359/16	147/73	266/08	0.09	1.91	16.46	D	transpressive
D3b	6	185/21	277/06	022/68	0.67	2.67	6.03	D	pure compressive
D2a	50	317/05	062/69	226/21	0.09	1.91	14.63	C	transpressive
D2b	69	306/05	216/01	111/84	0.75	2.75	7.27	A	pure compressive
D1a	34	089/05	246/85	359/01	0.31	1.69	9.88	B	pure strike-slip
D1b	10	101/15	197/17	332/67	0.71	2.71	7.62	C	pure compressive

dextral transpression zone along the western sector of the PKB in the Late Oligocene – Early Miocene (Fodor 1995; Marko et al. 1995, 2005). The activity of a brittle dextral transpression zone resulted in the final morphostructural character of klippen with long axes oriented in the NE-SW direction. Subvertical strike-slips and SE-dipping reverse faults are located along SW-NE contacts of the PKB with the Biele Karpaty Unit. Most of contacts of the Czorsztyn, Kysuca and transitional units are also subvertical strike-slips and NW or SE-dipping reverse faults. Record of younger tectonic events is less clear. Rotation of the σ_1 axis of the regional palaeostress field to the N-S direction is ascribed to a rigid counterclockwise rotation of the entire ALCAPA block during the Early Miocene by some 80° with a stable orientation of the σ_1 axis (Kováč et al. 1994; Kováč and Túnyi 1995; Marko et al. 1995; Kováč and Hók 1996). The N-S compression (Early – Middle Miocene) caused mainly formation of the sinistral strike-slip faults roughly parallel to the strike of the belt and rarely E-W reverse faults under the sinistral transpression. The next two tectonic events (Middle to Late Miocene) are marked by forming mainly strike-slip faults and normal faults as a result of the transtensive tectonic regime with NNE-SSW to NE-SW trending compression. Active clockwise rotation of the main compressional stress from N-S to NE-SW and inversion from the older transpression to the younger sinistral transtension were a result of NE-ward translation of the entire ALCAPA block (Marko et al. 1995; Kováč and Hók 1996). Normal faults oriented in NE-SW direction were created by the NW-SE extension during the last deformational phase under the extensional tectonic regime (Pontian – Pliocene). Finally, the klippen style was affected also by slope movements and some independent blocky klippen are obviously loose blocks transported downslope by landslides.

6. Conclusions

The studied area was formed during multistage ductile-brittle and brittle tectonic evolution that occurred in several deformation stages producing variable fold and fault structures. Probably the oldest stage was thrusting of the presently most external Kysuca Unit over the Czorsztyn and transitional units. Then macroscopic folding due to orthogonal layer-parallel shortening affected especially the Chmeľová region with well-bedded transitional successions, while the thick competent Vršatec-Javorník slab was steepened and partly overturned to the SE. This significant primary compressional stage was followed by transpression and formation of the positive flower structure during the Early to Middle Miocene. Numerous reverse and strike-slip faults truncated the stiff limestones sandwiched between incompetent strata and produced klippen of two distinct morphostructural types: 1) the Vršatec type formed by vertical strata obliquely cut by faults into variously large, lozenge-shaped blocks arranged in one straight zone; 2) the Chmeľová type with a more random arrangement of variously shaped klippen, dependent on which parts of pre-existing macrofolds (cores, limbs) were separated into klippen that slightly moved with respect to each other afterwards. The next brittle deformation regimes – transtension to extension – during the Middle Miocene to Pliocene times are recorded mainly by sinistral strike-slip and normal faults.

Acknowledgement

This work was supported by the Slovak Research and Development Agency under the contracts No.

APVV-LPP-0225-06 and APVV-0465-06, and by Comenius University under the contract No. UK/267/2007 and No. UK/297/2008.

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