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Petrophysical control on the mode of shaering in the sedimentary rocks and granitoid core of the Tatra Mountains during Late Cretaceous nappe-thrusting and folding, Carpathians, Poland

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ABSTRACT:

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In the Tatra Mts., the variability of structures within the granitoid rocks and their sedimentary complexes depends on the physical properties of the rocks, particularly on their porosity and sensibility to dissolution. In the relatively homogeneous and low porosity granitoid rocks, the shear surfaces are planar and smooth without damage zones around the shear planes. They did not develop open spaces during shearing, which prevented fluid migration and hydrotectonic phenomena. In the sedimentary rocks, mechanical, mostly bedding anisotropy controlled the geometry and morphology of the shear zones. High porosity and recurring changing in pore fluid pressure determined the cyclic character of the thrust-related shearing processes. Fluids appearing within the thrust-fault fissure played the key role in tectonic transport and selective mass-loss processes (hydrotectonic phenomena). The mass-loss process was an effect of mechanical disintegration, pressure solution and cavitation erosion. The multistage character of the thrusting processes resulted in a gradual increase in mass loss value and in geometrical complication of the shear zones. Within the Czerwone Wierchy Nappe, the minimum value of the mass-loss estimated from a restored cross-section is in the range of 15-50%.

Key words: Hydrotectonic phenomena, Mass loss, Pressure solution, Cavitation erosion, Tatra Mts.

INTRODUCTION

In the Tatra Mts., Late Cretaceous thrust-napping processes affected not only the rocks of the nappe units but also the crystalline core and its autochthonous sedimentary cover (e.g. ANDRUSOV 1968; KOTAŃSKI 1963; BAC-MOSZASZWILI & *al.* 1984). Shear stress generated due to basement shortening in the Fatricum and north Veporicum was responsible for the nappe-thrusting process in the Tatra Mts. (PLAŠIENKA & *al.* 1997). The deformation structures within the crystalline core formed under similar conditions and in the same stress field and do not have their equivalents in the sedimentary complexes.

The tectonic style of nappes in the transitional zone from the basement to the cover was often studied (e.g. EPARD & ESCHER 1996, KWON & MITRA 2006). The change in the geometry of structures in the cover nappes commonly reflects the inhomogeneous character of the deformed rocks caused e.g. by palaeofaults responsible for stress perturbation and formation of fault-related folds (Wissing & Pfiffner 2003). The aim of this paper is to show that the complex geometry of the nappe structures and thrust surfaces in the Tatra Mts. are inseparably connected with lithological heterogeneities of the deformed rocks, in particular with the presence of evaporites (so-called Rauhwacke) as mechanically weak detachment horizons at the basal thrusts of the nappes. The specific pattern of the Tatra Mts. nappes, as observed today, is a consequence of the hydrotectonic phenomenon (Jaroszewski 1982), which originated at the base of the nappes and was associated with large-scale mass-loss processes (Jurewicz 2003). In earlier interpretations (Bac-Moszaszwili & *al*. 1981), decrease in mass in the vicinity of the thrust was connected with pre-thrusting erosion, while the present author is of the opinion that this process originated during thrusting due to fluid migration associated with the hydrotectonic phenomenon (Jurewicz 2003, Jurewicz & Słaby 2004).

GEOLOGICAL SETTING

The Tatra Mts. are the northernmost part of the Central Western Carpathians. They are composed of a Variscan crystalline basement and its sedimentary complexes belonging to the Tatric-Fatric-Veporic nappe system (Text-fig. 1) (Andrusov 1968; Mahel' 1986; Plašienka & *al.* 1997). The crystalline core of the Tatra Mts. is composed of two older structural elements: the metamorphic sequences of the Western Tatra Mts. and the granitoid rocks of the High-Tatra Mts. (e.g. Putiš 1992; Janák 1994). The crystalline core of the Tatra Mts. is overlain by Mesozoic sedimentary sequences, which correlate well with Austroalpine units (Häusler & *al.* 1993; Plašienka & *al.* 1997). Three groups of structural units are composed of Mesozoic sedimentary strata (Kotański 1963): (1) the High-Tatric autochthonous sedimentary cover; (2) two High-Tatric nappes: the Czerwone Wierchy Nappe (divided into the Zdziary and Organy units) and the Giewont Nappe; (3) the Sub-Tatric nappes of Krížna and Choč. The nappe-thrusting and folding in the Tatra Mts. are of approximately Late Cretaceous age and were traditionally linked with the Mediterranean orogenic phase (Andrusov 1965). The Tatra massif is overlapped by carbonate deposits of the so-called Nummulitic Eocene and a post-orogenic Palaeogene flysch sequence (e.g. Bieda 1959; Gedl 1999). In the topographic sense the Tatra massif emerged at the surface due to its Miocene rotational uplift around the W-E horizontal axis (northerly tilting; Sokołowski 1959; Piotrowski 1978; Bac-Moszaszwili & *al.* 1984; Jurewicz 2000a). The youngest sediments in the area of the Tatra Mts. are related to Pleistocene glaciations and Holocene erosion-accumulation processes.

During Late Cretaceous–Eocene times, the Carpathian area formed part of a larger Alpine-Carpathian orogen formed by south-eastward subduction

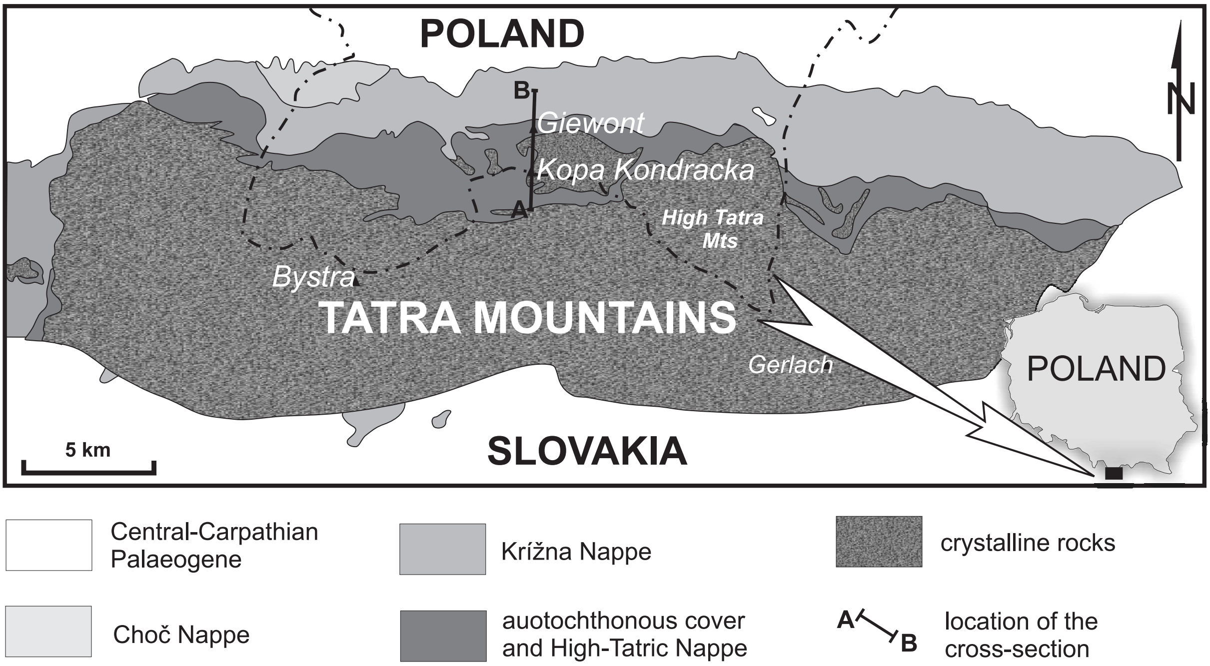

Fig. 1. The main geological tectonic structures of the Tatra Mts. (after Bac-Moszaszwili & *al*. 1979)

of the Penninic Ocean (135–55 Ma) and a later collision of the European and Adriatic continents (55-40 Ma; NEMČOK & NEMČOK 1994; NEMČOK & *al.* 1998). The age of Alpine thrusting and folding is progressively younger from south to north. The northward migration of nappes from the hinterland to the foreland is well documented by the diachronous position of the pre-orogenic flysch and the progressively younger ages of the sediments involved in the cover nappes towards the foreland (LEFELD & *al.* 1985; PLAŠIENKA 1996, 2003). As in the case of the crystalline core, the sedimentary cover was also deformed during Alpine thrusting and folding but, due to the different physical properties of the rocks, in a different manner.

TYPE AND ORIGIN OF SHEAR ZONES IN THE TATRA MTS.

During Early to Late Cretaceous times, the thinned continental crust of the basement of the Fatric-Tatric Basin showed a lateral rheological heterogeneity caused by lithospheric extension and rifting (cf. VAUCHEZ & *al.* 1998). This favoured the formation of low-angle anisotropy and consequently of major flat-lying thrusts and detachments (see GHEBREAB 1998). Above the roof thrust of the thrust system slightly disturbed strata may have been present, whereas imbricate structures and a hinterland dipping duplex could have formed below (see BOYER & ELLIOT 1982). Initially, assuming a simple model of folding, thrusting and duplex formation could have been complicated by the large lithological variability and rheological heterogeneity of the deformed rocks. When the subduction had completely consumed the basement of the more southerly sedimentary zones, the crystalline basement of the High-Tatric series also underwent compression and thrust-related shearing. The fact that crystalline rocks are also included in the nappes and that they were detached at depths of at least several (c. 10) kilometers (LEFELD & JANKOWSKI 1987), suggests that the detachment was preceded by compression, which resulted in reverse faulting (e.g. BAC-MOSZASZWILI & *al.* 1984). In some cases, reverse faults may have originated due to the changing of the sense of movement on originally normal faults. This is evidenced e.g. by the angle of 60° between the surface of the sedimentary contact of Seisian sandstones with the crystalline rocks and the Giewont Nappe thrust (BAC-MOSZASZWILI & *al.* 1979; JUREWICZ 2005). During later stages of the thrusting and folding the surface of this fault was deformed (see below).

To compare the deformation structures within the crystalline core and the sedimentary cover, the granitoids of the High Tatra Mts. are much more useful than the metamorphic sequences of the West Tatra Mts. Here, the granitoid rocks are younger, and, thus less deformed. The relatively homogeneous and isotropic structure of the granitoids is responsible for the geometry of the shear zone patterns.

With regard to their age, three groups of structures can be distinguished within the granitoid core of the High-Tatra Mts.: (a) pre-Alpine structures, (b) structures produced by Late Cretaceous nappe-thrusting and (c) structures brought about by the Neogene rotational uplift of the Tatra massif (JUREWICZ 2002; JUREWICZ & BAGIŃSKI 2005). Owing to the character and geometry of the deformation, the nappe-thrusting related fault and shear zones of the High-Tatra Mts. can be subdivided into three groups: (a) steeply-dipping shear zones comprising mylonites or cataclasites (Text-figs 2A, B), (b) low-angle slickensided faults (Text-fig. 2C) and (c) high-angle slickensided faults (JUREWICZ 2000b, 2002). GROCHOCKA-PIOTROWSKA (1970) additionally distinguished the so-called “uniform slip zones” composed of several parallel fault-planes, which can be included into the latter (c) group of structures. The cataclastic and mylonitic zones (a) formed, in general, during a pre-Alpine deformation stage, and were reactivated during the Neogene uplift as sinistral strike-slip faults or oblique normal-slip faults (305/60) (JUREWICZ 2002; JUREWICZ & BAGIŃSKI 2005). The high-angle slickensided faults (c) are genetically related to the rotational uplift in the Neogene (SOKOŁOWSKI 1959; PIOTROWSKI 1978; BAC-MOSZASZWILI & *al.* 1984; JUREWICZ 2002). These kinds of faults commonly occur within the sedimentary cover and nappe units (Text-fig. 2D), thus their ages are unequivocally younger than Late Cretaceous. The group (b) comprises low-angle and smooth slickensided faults, whose orientation points to their relationship with the Late Cretaceous thrusting event (JUREWICZ 2000a).

Within the Tatra granitoid core, most thrust surfaces and faults that can be linked with the Alpine folding are characterised by shallow dips transformable into original southern dips (i.e. preceding the Neogene tilting – JUREWICZ 2000a). An analysis of tectonic transport directions based on striae on such slickensides occurring within the crystalline rocks of a tectonic cap (so-called “Goryczkowa Island”) was made by BURCHART (1963). The low-angle slickenside faults from the granitoid core of the High-Tatra Mts. allowed a reconstruction of the Late Cretaceous stress field to be made (JUREWICZ 2000a). The structural analysis of the crystalline core and the nappe units which was proceeded by a back-tilting of the Tatra block by c. 40°, to a position it occupied prior to the Neogene rotation (BURCHART 1972; KRÁL’ 1977;

Piotrowski 1978; Kováč & *al.* 1994; Jurewicz 2000a, b), indicated the prevailing northern direction of tectonic transport. The NW direction is older than the N direction. This can be inferred both from the orientation of slickenside of striae within the granitoid core (Jurewicz 2000a), as well as from the distribution of bedding attitudes in the sedimentary complexes on Lambert-Schmidt stereogram plots (Jurewicz 2000 b).

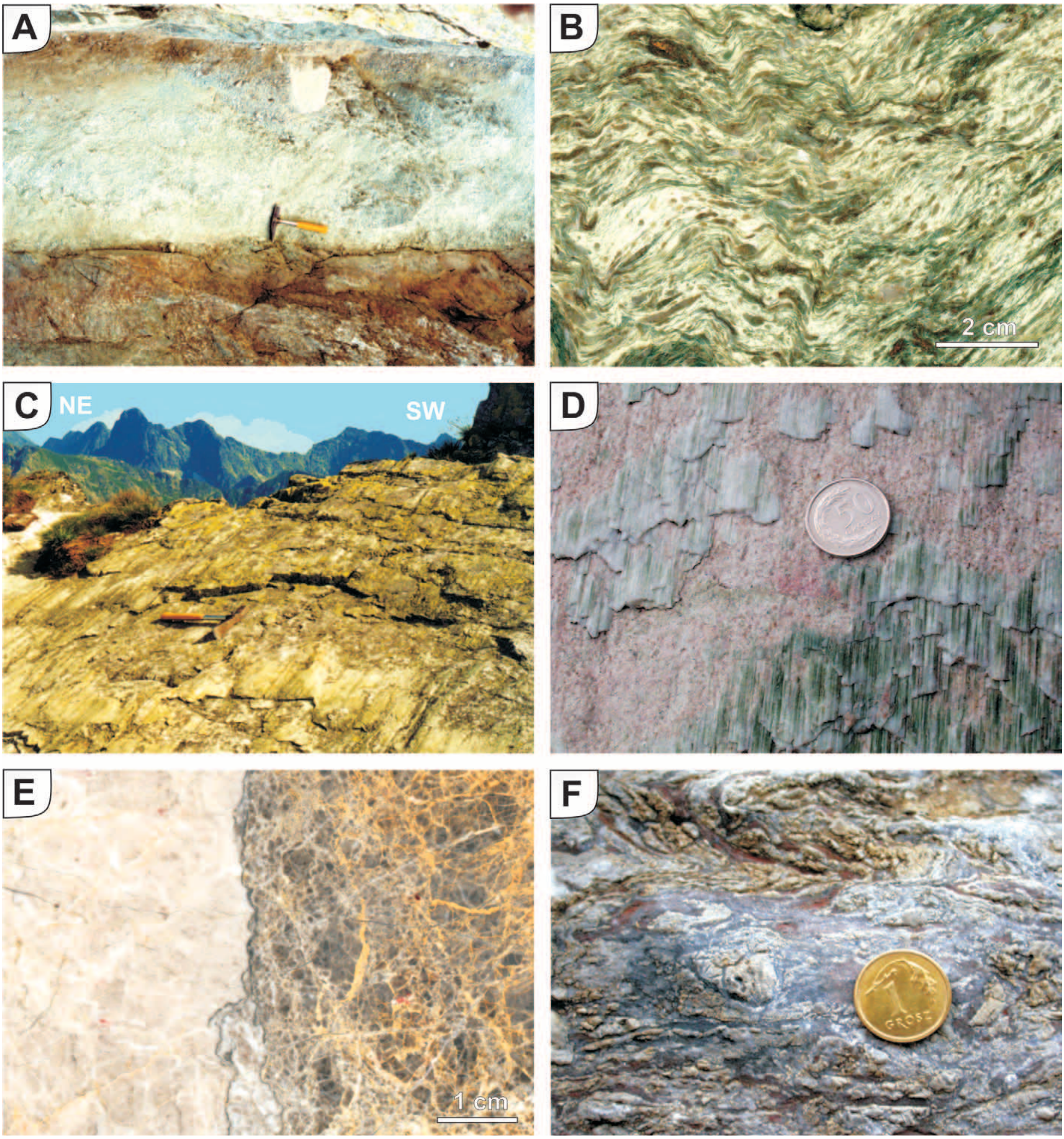

Fig. 2. Deformation structures in the Tatra Mts. **A** – very fine-grained tectonic gouge within the shear zone in granitoid rocks, Bandzioch Cirque (160/60), High Tatra Mts. (pre-Alpine deformation phase, reactivated during the Neogene). **B** – polished surface of the ductile-folded of foliation in granite mylonites within the lower part of the shear zone within the Bandzioch Cirque (160/60), High Tatra Mts. (pre-Alpine deformation phase). **C** – low-angle dipping fault plane coated with quartz and epidote (315/35), Zmarzła Pass, High Tatra Mts. (reverse fault forming during Late Cretaceous deformation phase, preceding the Tatra rotational uplift). **D** – surface of a normal fault coated with quartz and chlorite (290/70), Seisian sandstone, NW slope of the Ciemniak Mt., High-Tatric nappes (Neogene uplift related). **E** – stylolitic character of the contact between the Urgonian limestone of the High-Tatric nappes (pale) and Anisian dolomite of the KríÏna nappes (dark); Stoły Hill (Late Cretaceous deformation phase). **F** – strongly folded dolomite mylonite at the base of the Giewont Nappe, High-Tatric nappes (Alpine deformation phase)

The older NW striae were partly destroyed by younger, more northely directed striae and, currently can be observed on few slickenside planes. This may indicate that either a gradual change of the maximum principal (σ_1) stress orientation from the NW to N position took place during thrusting, or that a counter-clockwise rotation of the basement occurred under conditions of a stable stress field of constant orientation (JUREWICZ 2000b). Other evidence for the basement counter-clockwise rotation during Late Cretaceous folding and thrusting or for the changing dirrection of thrusting was found from the analysis of bedding attitudes. The latter analysis points to the fact that the higher and earlier overthrust units (the Krížna and High-Tatric nappes) show signs of a NW-directed compression whereas the rocks of the later deformed autochthonous sedimentary cover display a N compression orientation (JUREWICZ 2000b). Structural investigations within the crystalline massif and sedimentary cover (JUREWICZ 2000a, b) made it possible to evaluate the angle of post-Turonian and pre-Eocene nappe-folding counter-clockwise rotation around a vertical axis to be *c.* ~45°.

The *en-bloc* rotation of the basement during the nappe-thrusting seems to have only slightly influenced the orientation of the slickenside surfaces within the crystalline core. Because the rocks of the crystalline core were the last to be incorporated into the Late Cretaceous thrusting, it can be assumed that their activation did not require as many stages as in the case of the shear zones within the sedimentary complexes. Likewise, they were not subjected to deformations during the younger tectonic events, in which the stress field did not favour possible reactivation of the Alpine slickenside surfaces; at that stage they attained an almost semi-perpendicular position to the plane of the shear stress.

The shear zones in the sedimentary complexes that can be linked with nappe thrusting are typically devoid of slickenside striae. Their surfaces are not planar, but of complex morphology, and in some cases (e.g. in the floor of the Zdziary Unit) show signs of folding. Deformational structures at the base of the nappes, ductile in nature, are extremely variable and show signs of multiple activation. They are thus not suitable for kinematic analysis of the tectonic transport directions and reconstruction of the stress field.

COMPARATIVE ANALYSIS OF SHEAR ZONE DEFORMATIONS IN THE TATRA MTS. GRANITOID CORE AND SEDIMENTARY COMPLEXES

When compared to the sedimentary carbonate rocks, the granitoids show both similarities and differences with regard to their physical properties influencing the course of the deformation processes. The granitoids of variable mineral composition, including quartz, feldspars and micas, show typically in laboratory tests a larger uniaxial compression strength than the carbonate rocks (granite: c. 60-230 MPa; carbonate: c. 15-130 MPa), and a distinctly lower and rather uniform porosity (granite: c. 0.4-3.7%; carbonate: c. 0.1-30%) (PINIŃSKA 1997, 2000). The key factor controlling the deformation processes in the Tatra Mts. sedimentary rocks was lithological variability. The presence or absence of bedding in the carbonate rocks, variable susceptibility to pressure solution, and different proportions of marl and clay intercalations distinctly influenced the rock anisotropy. One of the many reasons for the geometric complication of the tectonic structures in the Tatra Mts. may have been thickness changes due to sedimentation on rotated blocks. Such a situation may be observed on the Mt. Kominy Tylkowe in the High-Tatric autochthonous cover, where KOTAŃSKI (1959) and RUBINKIEWICZ & LUDWINIAK (2005) ascertained thickness reduction of the Lower and Middle Triassic deposits by c. 30-50%. The High-Tatric stratigraphic succession shows indirect evidence of synsedimentary listric normal faulting associated with the rotation of beds in the hanging wall from horizontal to a steeper dip (JUREWICZ 2005). The formation of listric faults resulted in the propagation of fault-related synclines (see KHALIL & MCCLAY 2002) that developed further at younger tectonic stages.

The granitoid core of the High-Tatra Mts. bears numerous slickensides. Their surfaces are planar, smooth and coated with quartz, epidote or chlorite. Investigation of fluid inclusions in syn-kinematically grown quartz slickenfibres on these faults indicated stable P-T conditions of the deformation. Quartz crystallized under pressures of c. 1.45-1.7 kbar (145-170 MPa) and temperatures of c. 212-254°C (JUREWICZ & KOZŁOWSKI 2003). These values allow estimation of the depth of deformation along the Late Cretaceous faults at c. 6-7 km. The pressure and temperature within the sedimentary rocks that must have been deformed at shallower depths, proved to be more variable. The temperatures obtained from the shear zone within the High-Tatric nappes, determined from chlorite and feldspar thermometers, varied in the range 300-350°C (JUREWICZ & SŁABY 2004). The twinning in dolomite also indicates temperatures in excess of 300°C. In a similar situation, a major dispersion of temperature values (213 to 471°C) and thus of pressure (20-540 MPa) was found by MILOVSKÝ *& al.* (2003) from investigation of fluid inclusions in the basal cataclasites of the Muráň Nappe, part of the Silicicum cover nappe system (southern part of the Central Western Carpathians). Thus the P-T conditions of the deformation depended not only on the value of the geothermal gradient (cf. JUREWICZ & BAGIŃSKI 2005) but on numerous other factors.

In the Tatra Mts., the basal shear zones of the nappes are in general devoid of slickensides. Their morphology is usually complex, uneven and rough. In many cases, e.g. on the Stoły Hill, the floor thrust of the nappe is of a stylolitic character and it lacks any conventional shear sense (Text-fig. 2E) (cf. BAC-MOSZASZWILI & *al.*1981). A different case is the floor thrust of the Giewont Nappe, where typical dynamometamorphic structures such as foliation, stretching lineation and pressure solution-related veins, strain shadow and neoformed minerals, can be found (JUREWICZ 2003), most of them being subsequently strongly deformed (Text-fig. 2F).

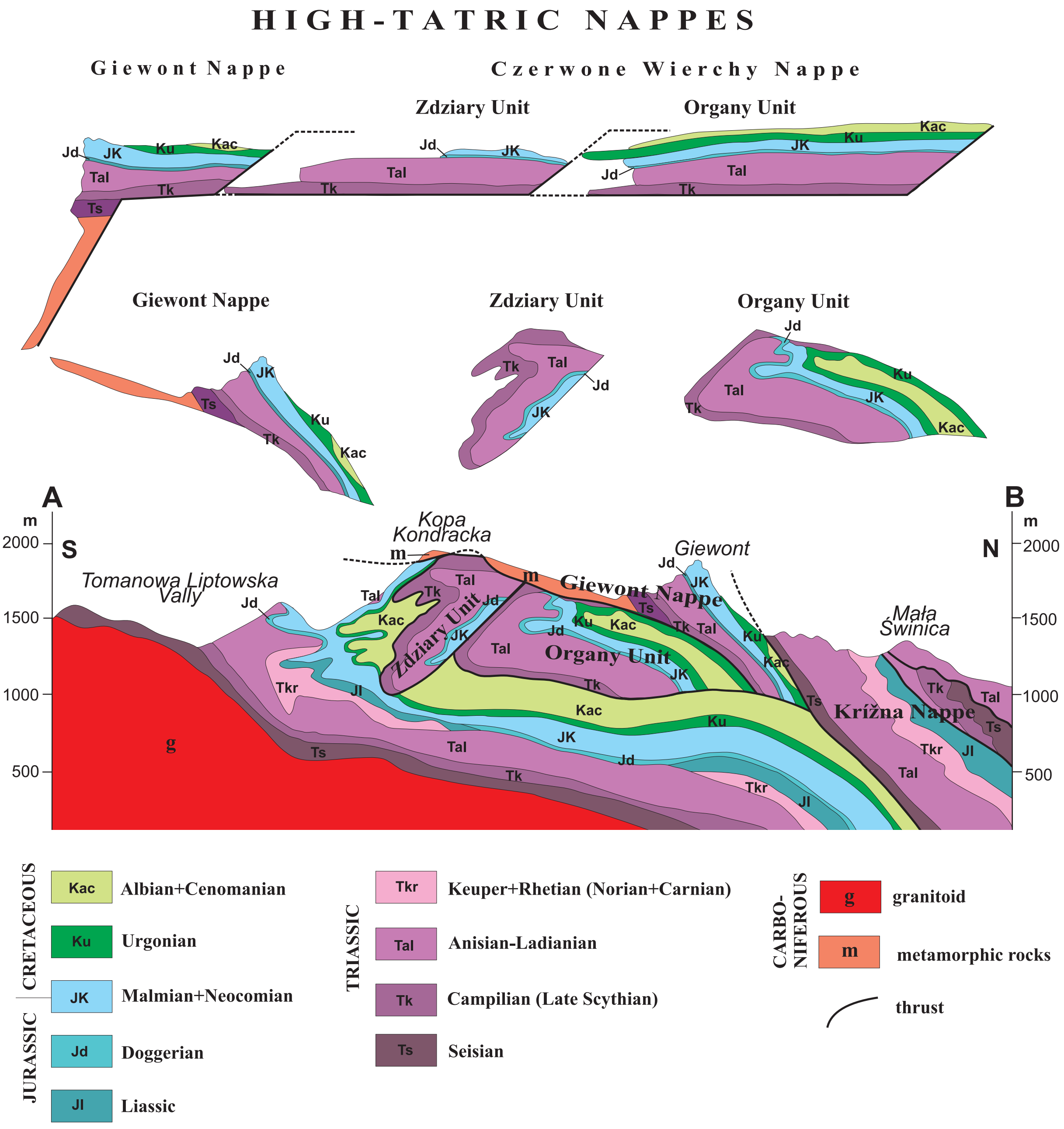

Fig. 3. Retro-deformation of the High Tatric nappes to the pre-folding and pre-thrusting stage. A – reconstruction showing minimum value of mass-loss based on cross-section by BAC-MOSZASZWILI & *al.* 1979, simplified (C); B – Isolated units of the High-Tatric nappes (note that in the Giewont Nappe the originally normal fault within the crystalline core later became a thrust surface)

Nappe thrusting in the Tatra Mts. probably occurred under submarine conditions, resulting in full saturation of the rocks with seawater and leading to an apparent decrease in weight and internal friction angle at the soles of the thrusts. Thus the nappe transport must have been facilitated by pulses of increased pore pressure within the floor thrust (PRICE 1975; KENNEDY & LOGAN 1997; JUREWICZ 2003). Increasing tectonic compression led to pore pressure building up, which resulted in a fall of effective stress, and the formation of brittle failure of rocks in the damage zone. The newly opened shear fissures became the pathway for high pressure-driven, vigorous migration of fluids along the base of the nappes, making them almost frictionless and prone to displacement. Following the tectonic displacement, the stress dropped and the nappe motion was arrested for some time, enabling mineralisation and cementation to occur in the basal the shear zone. At the next stage of the process, increasing compression made the pore pressure rise once again, resulting in a decrease in effective stress and the formation of a damage zone. Thus, the next cycle could start. In each successive cycle, brittle failure and ductile deformation occurred (see KENNEDY & LOGAN 1997). In this way, the nappe-thrusting was a repeatedly re-activated, reccurent process controlled by successively increasing and decreasing tectonic stress level, and by the concomitant increases and decreases in pore pressure, breaking down the cohesion and strength of the rock.

The structural geometry of the thrust units in the Tatra Mts. is not that of a simple duplex (cf. e.g. BOYER & ELLIOT 1982). Its complexity is e.g. due to relatively intense, synclinal internal folding and the overturned position of some of the component thrust slices (Text-fig. 3).

The present author's field and laboratory investigations revealed that the key factor that influenced the geometrical complexities of the nappe structure was a large-scale mass-loss process operating along the thrust surfaces (JUREWICZ 2003). In specific cases, mass-loss within thrust fault zones led to "consumption" of the wall-rock, which caused the stress relax-

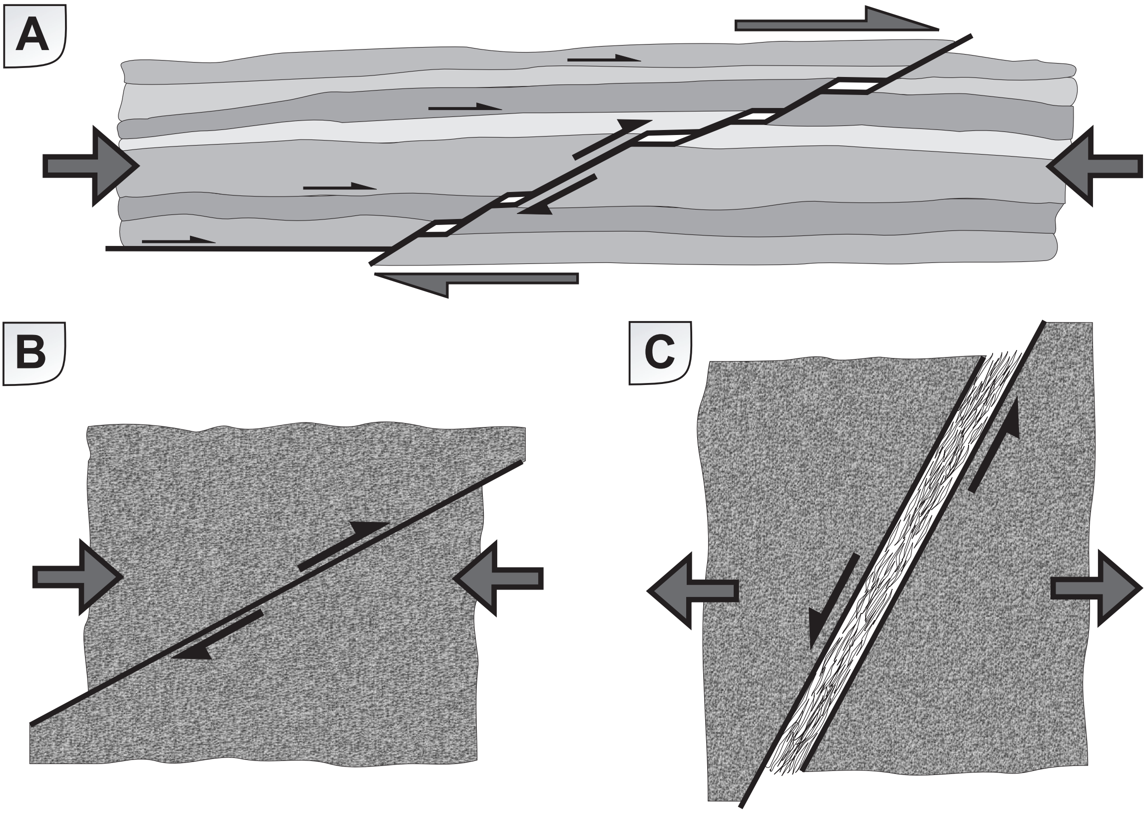

Fig. 4. Scheme showing the different geometry of the shear zones in stratified sedimentary rocks (A) and in homogeneous granitoid rocks (B, C). **A** – within the stratified sedimentary rocks the morphology of the shear surface is step-like and non-planar. During the thrusting motion open spaces ("chambers") could originate at releasing bends of shear surfaces. The presence of chambers leads to local fluctuation in fluid pressure during fluid migration. **B** – within the granitoid core, along flat, smooth and tightened shear plane the migration of fluid is difficult. **C** – in opened fissures of steeply-dipping normal fault the fluid is free to migrate, thus fluctuation in fluid pressure is very low.

ation without displacement. Such a kind of shear zone was described as a “ravenous” fault (JUREWICZ & SŁABY 2004). One of the main mechanisms for the mass-loss may have been brecciation of the wall-rocks due to hydraulic fracturing and washing out the floating rock fragments. Besides brecciation and mylonitization, pressure solution and hydrothermal activity responsible for dissolution creep may also have been a factor controlling internal erosion within the shear zones (see GRATIER & *al.* 1999; RENARD & *al.* 2000). Fluids may cause a change in the predominant mechanism of deformation due to hydrolytic weakening or crack seal-slip phenomena (PETIT & *al.* 1999). The presence of fluids would have meant that large volumes of rocks could have been moved in the form of suspension and solution. Fluids, released to the shear zone and forming a suspension with low friction values, could have acted as a “water pillow” facilitating the movement of the nappe (JUREWICZ 2003). The existence of such a “water pillow” may be related to the over-pressured fluid within the shear zone (GUDMUNDSSON 2001). The effect of reversing fluid pressure in highly permeable rocks separating water from water-saturated fault breccia (“fault slurry”) was described by KOPF (2003) on the basis of an experiment. He inferred “that the water-saturated fault-breccia restricts flow through a porous rock, essentially acting as a one-way valve”. It means that the water could flow freely from pores and fractures into the fault fissure but could not leave it because the water-saturated fault-breccia acted as a diaphragm.

All the above fluid-related processes were termed “hydrotectonic phenomena” by KOPF (1982, 2003) and JAROSZEWSKI (1982). According to KOPF (2003), “chambers and bottlenecks” form “between noncongruent undulatory surfaces of opposing wall-rocks” during shear displacement along non-planar faults. During the thrust motion, the volume of both the newly opened and earlier formed chambers alternately increased and decreased. For this reason, chambers filled with fluid could temporarily be over- or under-pressurised. The squeezing of fluids within the fault fissures resulted in cavitation phenomena and cavitation erosion (JUREWICZ & *al.* submited). The cavitation refers to the repeated cycles of growth and collapse of bubbles in a liquid, due to vigorous local pressure fluctuations (PREECE 1979). Within the fault fissure, local pressure fluctuations could be caused by opening the chambers due to incremental tectonic motions and the related abrupt changes in the flow regime and geometry. During collapse of the bubbles, large stress pulses are generated (FRENKEL 1955) impinging on the wall-rocks in contact with the liquid.

This mechanism of internal erosion within a shear zone at the nappe’s floor thrust often enhances and takes advantage of rock anisotropy, particularly bedding, which can significantly influence the geometry of the growing shear surface (Text-fig. 4A). This mechanism is restricted to the Tatra Mts. sedimentary rocks. The main cause for the lack of a comparable process within the High Tatra granitoid core is that the planar geometry of most of the fault surfaces did not facilitate opening of empty spaces during the thrust motion, thus preventing massive fluid flow (Text-fig. 4B). Moreover, due to the low solubility and low porosity of granites, as well as the absence of efficient fluid sources, the hydrotectonic phenomena and related cavitation erosion were not active in them.

The hydrotectonic phenomena within the sedimentary complexes of the Tatra Mts. occurred only during the Alpine Late Cretaceous nappe-thrusting stage, because high fluid overpressures were favoured in a compressional tectonic regime, accompanied by the highest amplitude of fluid-pressure cyclic changes (SIBSON 2004). The escape of fluids along shallow dipping thrust-related shear zones driven by horizontal compression was probably much slower than along the steeply dipping normal faults and shear zones (Text-fig. 4). Attaining high fluid pressure was not favoured in the extensional regime related to the Neogene uplift which activated or brought about the formation of the steeply dipping fault/shear zones (Text-fig. 4C). In open high-angle fissures, the fluids were free to migrate, due mostly to the hydraulic gradient (PRICE 1975; SIBSON 1996), resulting in the development of either slickensided normal faults (Text-fig. 2D) or tectonic breccia zones.

To analyze the geometry of deformation in the High-Tatric nappes and to estimate the minimum value of mass-loss due to the thrust-napping processes, the cross-section of the High-Tatric nappes (after BAC-MOSZASZWILI & *al.* 1979) was unfolded and restored to the pre-thrusting situation (Text-fig. 3). Within the Czerwone Wierchy Nappe, the minimum value of the mass-loss estimated from a manually retrodeformed cross-section is in the range of 15 to 50%. The restoration of the pre-folding structures was made on the assumption that the synclinal geometry of the component thrust slices was an effect of late-folding of pre-existing duplexes.

Beside the tectonic processes, the thickness reduction in the sedimentary complexes involved could have been caused by chemical compaction, assessed by ŁUCZYŃSKI (2001) for the Middle Jurassic part of the High-Tatric series at c. 20 to 70%, but this kind of process did not disturb the overall structural geometry of the thrust units.

GRAVITY SLIDING OR COMPRESSIONAL SHEARING?

The concept of “down-dip”gravity sliding as the driving mechanism for the emplacement of nappes in the Tatra Mts. was introduced in the 1960s by KOTAŃSKI (1961, 1963) and later questioned by BAC-MOSZASZWILI & *al.* (1984). GOREK & VEIZER (1965) also supplied some arguments against the gravity sliding, emphasizing that the large crystalline core within the Giewont Nappe precluded the gravity origin of this structure. After a back-tilting of the Tatra block to a position prior to Miocene rotational uplift (GRECULA & ROTH 1978; PIOTROWSKI 1978; BAC-MOSZASZWILI & *al.* 1984; JUREWICZ 2000a), the floor thrusts of the nappes within the sedimentary complexes and the related fault planes in the Tatra granitoid core (JUREWICZ 2000a) attain southerly dips. It follows from this that the nappes must have been transported “upward” in a compressive tectonic regime. Gravity sliding, on the other hand, usually occurs under an extensional tectonic regime (cf. an example from the Małe Pieniny Mts. – JUREWICZ 1997), whereas the deformation structures observed in the High-Tatric and Krížna nappes must have originated in a compressional regime, as can be inferred from a cross-section of Text-fig. 3 (see JUREWICZ 2003, 2005).

The nappe thrusting in the Tatra Mts. probably took place under submarine conditions, at full saturation of the rocks with seawater, which must have significantly influenced the values of the effective lithostatic, hydrostatic and pore pressures (see SIBSON 1996, 2000). The submersion was responsible for the apparent decrease in the weight of the nappe. Tectonic movement along the shear zones was easier because the presence of fluids at the sole thrusts resulted in a close-to-zero value of the internal friction angle. Tectonic transport could have taken place at even insignificant differential stress values ($\sigma_1 - \sigma_3$), irrespective of the high or low value of σ_1. The small values of differential stress necessary for displacement may be responsible for the non-linear character of the tectonic movement of the nappe (JUREWICZ 2003), which is reflected in the oblique directions of tectonic transport of the Giewont Unit (from the SSE) in relation to the Czerwone Wierchy Unit (from the SSW – see BAC-MOSZASZWILI & *al*. 1984). According to KOTAŃSKI (1963) this phenomenon was connected with gravity sliding of nappe units into the morphological depression of Goryczkowa-Jawor. The direction of fluid migration controlled by the hydraulic gradient (see PRICE 1975; KNIPE 1989; SIBSON 1996) must have followed the direction of the tectonic transport. It is only in these conditions that a “water pillow” on which the nappe was “floating” could originate and thus make the thrusting possible (Text-fig. 4A). This is why the cyclic fluctuation in the pore pressure caused the nappe to move and why the local fluctuation in the fluid pressure was responsible for the mass-loss. The crucial role of fluids within the thrust zones made the compressive model for the nappe thrusting in the Tatra Mts. more probable. The relatively great depth inferred for the thrusting of the Czerwone Wierchy Nappe (6–7 km for the upper part of the granitoid rocks minus the thickness of the autochthonous High-Tatric sedimentary cover c. 1.1 to 2.4 km, according to KOTAŃSKI 1959) and the significant value of the lithostatic pressure also seem to preclude a gravity sliding model.

The model described above concerns the High-Tatric nappes and the Polish part of the Tatra Mts., and not necessarily the entire Tatric-Fatric nappe system, where local gravitational sliding phenomena were recognized by PLAŠIENKA & PROKEŠOVÁ (1996) and PLAŠIENKA & *al.* (1997).

CONCLUSIONS

The different styles of tectonic structures that developed in the granitoid core of the Tatra Mts and in its autochthonous sedimentary cover and nappes, depended on the petrophysical differences between the two rock complexes, particularly those concerning the porosity and solubility. The bedding anisotropy of the sedimentary rocks affected the geometry of the thrust-related shear zones and their selective damage. The fluid-driven hydrotectonic phenomena, taking place within the shear fissures, played the key role in the tectonic transport and in the mass-loss processes, both being cyclic in nature. The mass-loss must have resulted from mechanical disintegration of rock, from pressure solution and cavitation erosion. The cyclic character of the thrusting motion and the associated processes caused the progressive involvement of new parts of the wall-rocks into each new cycle and was responsible for the increasingly strong mass-loss along the thrust zone. Within the Czerwone Wierchy Nappe, the minimum value of the mass-loss was estimated from a retro-deformed cross-section as ranging between 15 and 50%. In the Tatra Mts., the mass loss processes were inseparably related to the complexities of the geometry of the thrust faults and nappes; both processes interacting with each other. As the result, the nappes in the Tatra Mts. do not show the characteristics of typical duplexes.

In the relatively homogeneous granitoid rocks, the shear surfaces are flat, smooth, coated with quartz, epidote and/or chlorite, without damage zones around the shear planes. Such shear planes devoid of open spaces prevented fluid migration, so that the hydrotectonic phenomena could not have occurred. Because of the isotropic character of the granitoid core rocks, during the thrusting processes the fault planes were not distorted as they were in the sedimentary cover, thus the reactivation of the displacement occurred only along older planes.

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REFERENCES

Andrusov, D. 1965. Aperću générale sur la géologie des Carpathes occidentales. *Bulletin de la Société Géologique de la France*, **7**, 1029-1062.

— 1968. Grundriss der Tectonik der Nördlichen Karpaten. 188 pp. *Veda*, Bratislava.

Bac-Moszaszwili, M., Gamkerlidze, I. P., Jaroszewski, W., Schroeder, E., Stojanov, S. & Tzankov, T.V. 1981. Thrust zone of the Krížna Nappe at Stoły in Tatra Mts (Poland). *Studia Geologica Polonica,* **68**, 61-73.

Bac-Moszaszwili, M., Burchart, J., Głazek, J., Iwanow, A., Jaroszewski, W., Kotański, Z., Lefeld, J., Mastella, L., Ozimkowski, W., Roniewicz, P., Skupiński, A. & Westfalewicz-Mogilska E. 1979. Geological map of the Polish Tatra Mts, 1:30000 scale. *Instytut Geologiczny*; Warszawa.

Bac-Moszaszwili, M., Jaroszewski, W. & Passendorfer, E. 1984. On the tectonics of Czerwone Wierchy and Giewont area in the Tatra Mts., Poland. *Annales Societatis Geologorum Poloniae*, **52**, 67-88. [*In Polish with English summary*]

Bieda, F. 1959. Nummulite fauna in the Tatra Eocene. *Biuletyn Instytut Geologicznego*, **141**, 5-13.

Boyer, S.E. & Elliot, D. 1982: Thrust systems. *American Association of Petroleum Geologist Bulletin*, **66**, 1196-1230.

Burchart, J. 1972. Fission-track age determination of accessory apatite from the Tatra Mts., Poland. *Earth and Planetary Science Letters*, **15**, 418-422.

Epard J.L. & Escher A. 1996. Transition from basement to cover: a geometric model. *Journal of Structural Geology*, **18**, 533-548.

Frenkel, J. 1955. Kinetic theory of liquids. Dover, New York.

Gedl, P. 1999. The age of base and top of the Podhale Palaeogene flysch (Central Carpathians, Poland), based on dinocysts. *Bulletin of the Polish Academy of Sciences, Earth Sciences*, **47**, 77-102.

Ghebreab, W. 1998. Tectonics of the Red Sea region reassessed. *Earth Science Reviews*, **45**, 1-44.

Gorek A. & Veizer J. 1965. Der Character der alpinen Tectonik in der Hohen Tatra. *Geologicky Sbornik Slovenskej Akadémie Vied*, **16**, 265-272.

Gratier, J.P., Renard, F. & Labaume, P. 1999. How pressure solution creep and fracturing process interact in the upper crust to make it behave in both a viscous and brittle manner. *Journal of Structural Geology*, **21**, 1189-1197.

Grecula, P. & Roth, Z. 1978. Kinematic model of the West Carpathians. *Sbornik Geologickych Vĕd, Geologie,* **32**, 49-73.

Grochocka-Piotrowska, K., 1970. Photointerpretation and genesis of the disjunctive structures in the granite massif of the Polish Tatra Mts. *Acta Geologica Polonica*, **20**, 365-411. [*In Polish with English summary*]

Häusler, H., Plašienka, D. & Polák, M. 1993. Comparision of Mesozoic succesions of the Central Eastern Alps and the Central Western Carpathians. *Jahrbuch der Geologischen Bundesanstalt*, **136**, 715-739.

Janák, M. 1994. Variscan uplift of the crystalline basement, Tatra Mts, Central West Carpathians: evidence from ^{40}Ar/^{39}Ar laser probe dating of biotite and P-T paths. *Geologica Carpathica*, **45**, 239-300.

Jaroszewski W., 1982. Hydrotectonic phenomena at the base of the KriÏna nappe, Tatra Mts. *In*: M. Mahel' (*Ed*.), Alpine structural elements: Carpathian-Balkan-Caucasus-Pamir orogene zone, pp. 137-148. *Veda*; Bratislava.

Jurewicz, E. 2000a. Tentative reconstructions of the stress axes from the thrust-folding stage in the Tatra Mts. on the basis of slickensides in the granitoid core, southern Poland. *Przegląd Geologiczny*, **48**, 239-246. [*In Polish with English summary*]

— 2000b. Tentative correlation of the results of structural analysis in the granitoid core and nappe units of the Tatra Mts., southern Poland. *Przegląd Geologiczny*, **48**, 1014-1018. [*In Polish with English summary*]

— 2002. Geometric analysis of steep dipping dislocations within the granitoid core in the Polish part of the Tatra Mts. *Annales Societatis Geologorum Poloniae,* **72**, 89-98.

— 2003. Multistage evolution of the shear zone at the base of the Giewont Unit, Tatra Mountains (Poland). *Geologica Carpathica*, **54**, 337-351.

— 2005. Geodynamic evolution of the Tatra Mts. and the Pieniny Klippen Belt (Western Carpathians): problems and commens. *Acta Geologica Polonica*, **55**, 293-338.

Jurewicz, E. & Bagiński, B. 2005. Deformation phases in the selected shear zones within the Tatra Mts granitoid core. *Geologica Carpathica,* **56**, 17-28.

Jurewicz, E., Gireń B. & Steller J. (submited) Cavitation erosion – a possible cause of the mass loss within thrust zones in the Tatra Mts., Poland. *Journal of Structural Geology*.

JUREWICZ, E. & KOZŁOWSKI, A. 2003. Formation conditions of quartz mineralisation in the mylonitic zones and on the slickenside fault planes in the High Tatra granitoids. *Archiwum Mineralogiczne*, **54**, 65-75.

JUREWICZ, E. & SŁABY, E. 2004. The Zadnie Kamienne "ravenous" shear zone (High-Tatric nappe) – conditions of deformation. *Geological Quarterly*, **48**, 371-382.

KHALIL, S.M. & MCCLAY, K.R. 2002. Extensional fault-related folding, northwestern Red Sea, Egypt. *Journal of Structural Geology*, **24**, 743-762

KENNEDY, L.A. & LOGAN, J.M., 1997: The role of veining and dissolution in the evolution of fine-grained mylonites: the McConnell thrust, Alberta. *Journal of Structural Geology*, **19**, 785-797.

KOPF, R.W. 1982. Hydrotectonics: Principles and Relevance: U.S. Geological Survey Open-File Report, 82-307, 30 p.

— 2003. The hydrotectonic hypothesis: a tectonically-activated hydraulic system. Unpublished manuscript donated to the U.S. Geological Survey, 38 pp.

KOTAŃSKI, Z. 1959. Stratigraphical sections of the High-Tatric Series in the Tatra Mts. *Biuletyn Instytutu Geologicznego*, **139**, 1-139. [*In Polish with English summary*]

— 1961. Tectogénèse et reconstitution de la paléogéographie de la zone haut-tatrique dans les Tatras. *Acta Geologica Polonica*, **11**, 187-467. [*In Polish with French summary*]

— 1963. New elements in the structure of Czerwone Wierchy massif. *Acta Geologica Polonica*, **13**, 149-198.

KOVÁČ, M., KRÁĽ, J., MÁRTON, E., PLAŠIENKA, D. & UHER P. 1994. Alpine uplift history of the Central Western Carpathians: geochronological, paleomagnetic sedimentary and structural data. *Geologica Carpathica*, **45**, 83-96.

KRÁĽ, J. 1977. Fission track ages of apatites from some granitoid rocks in West Carpathians. *Geologický Zborník – Geologica Carpathica*, **28**, 269-276.

LEFELD, J., GAŹDZICKI, A., IWANOW, A. KRAJEWSKI, K. 1985. Jurrasic and Cretaceous lithostratigraphic units of the Tatra Mts. *Studia Geologica Polonica*, **84**, 1-86.

LEFELD, J. & JANKOWSKI, J. 1985. Model of deep structure of the Polish Central Carpathias. *Publications of the Institute of Geophysics Polish Academy of Sciences*, **A-16**. 175, 593-614.

ŁUCZYŃSKI, P. 2001. Pressure-solution and compaction of condensed Middle Jurassic deposits, High Tatric series, Tatra Mts. *Geologica Carpathica*, **52**, 91-102.

MAHEĽ, M. 1986. Geologická stavba československých Karpat. (1) Paleoalpínske jednotky, 503 pp. *Veda*; Bratislava.

MILOVSKÝ, R., HURAI, V., PLAŠIENKA, D. & BIROŇ, A. 2003. Hydrotectonic regime at soles of overthrust sheets: textural and fluid inclusion evidence from basal cataclasites of the Muráň nappe (Western Carpathians, Slovakia). *Geodinamica Acta*, **16**, 1-20.

NEMČOK, M. & NEMČOK, J. 1994. Late Cretaceous deformation of the Pieniny Klippen Belt, West Carpathians. *Tectonophysics*, **239**, 81–109.

NEMČOK, M., POSPÍŠIL, L., LEXA, J. & DONELICK, R.A. 1998. Tertiary subduction and slab break-off model of the Carpathian-Pannonian region. *Tectonophysics,* **295**, 307-340.

PETIT, J. P., WIBBERLEY, C. A. J., RUIZ G., 1999. "Crack-seal", slip: a new fault valve mechanism? *Journal of Structural Geology,* **21**, 1199-1207.

PINIŃSKA, J. 1997. Właściwości wytrzymałościowe i odkształceniowe skał. Część II. Skały magmowe, osadowe i metamorficzne regionu Sudetów, 296 pp. *INVIT*; Warszawa.

— 2000. Właściwości wytrzymałościowe i odkształceniowe skał. Część III. Jura Krakowsko-Częstochowska, 221 pp. *INVIT*; Warszawa.

PIOTROWSKI, J. 1978. Mesostructural analysis of the main tectonic units of the Tatra Mts. *Studia Geologica Polonica*, **55**, 1-80. [*In Polish with English summary*]

PLAŠIENKA, D. 1996. Mid-Cretaceous (120-80 Ma) orogenic processe in the Central Western Carpathians: brief review and interpretation of data. *Slovak Geological Magazine*, **3-4**, 319-324.

— 2003. Development of basement-involved fold and thrust structures exemplified by the Tatric-Fatric-Veporic nappe system of the Western Carpathians (Slovakia). *Geodynamica Acta*, **16**, 21-38

PLAŠIENKA, D., GRECULA, P., PUTIŠ, M., KOVÁČ, M. & HOVORKA, D. 1997. Evolution and structure of the Western Carpathians: an overview. *In*: GRECULA P., PUTIŠ M. & HOVORKA D. (*Eds*), Geological evolution of the Western Carpathians, pp. 1-24. *Mineralia Slovaca – Monograph*, Bratislava.

PLAŠIENKA, D. & PROKEŠOVÁ, R. 1996. Towards an evolutionary tectonic model of the Krížna cover nappe (Western Carpathians, Slovakia). *Slovak Geological Magazine,* **3-4**, 279-286.

PREECE C.M., 1979. Cavitation Erosion. *In*: Treatise on Materials Science and Technology, 16 "Erosion", p. 249. *Academic Press*; New York.

PRICE N.J. 1975. Fluids in the crust of the Earth. *Science Progress*, **62**, 59-87.

PUTIŠ, M. 1992. Variscan and Alpidic nappe structures of the Western Carpathian crystalline basement. *Geologica Carpathica*, **43**, 369-380.

RENARD, F., GRATIER, J.P. & JAMTVEIT, B. 2000. Kinetics of crack-sealing, intergranular pressure solution, and compaction around active faults. *Journal of Structural Geology*, **22**, 1395-1407.

RUBINKIEWICZ, J. & LUDWINIAK, M. 2005. Fracture and fault development in the Werfenian quartzitic sandstones – a case study from the autochtonous cover of the Tatra Mts. (Poland). *Annales Societatis Geologorum Poloniae*, **75**, 171-187.

SIBSON, R.H. 1996. Structural permeability of fluid-driven fault-fracture meshes. *Journal of Structural Geology*, **18**, 1031-1042.

— 2000. Fluid involvement in normal faulting. *Journal of Geodynamics,* **29**, 469-499.

SOKOŁOWSKI, S. 1959. Geological map of the Nummulitic Eocene Region – Northern Margin of the Polish Tatra. *Biuletyn Instytutu Geologicznego*, **149**, 197-212. [*In Polish with English summary*]

VAUCHEZ, A., TOMASI, A. & BARRUOL, G. 1998. Rheological heterogeneity, mechanical anisotropy and the deformation of the continental lithosphere. *Tectonophysics,* **296**, 61-86.

WISSING S.B. & PFIFFNER O.A. 2003. Numerical models for the control of inherited basin geometries on structures and emplacement of the Klippen nappe (Swiss Prealps). *Journal of Structural Geology*, **25**, 1213–1227.

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