Paleopiezometry – the new investigation method applied to the Penninic suture zone in comparison to the Meliata-Hallstatt suture zone

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The method of paleopiezometry reveals new pleopiezometric data of differential stresses σ (σ1 – σ3; MPa) within the calcite veins in outcrops with developed fold structure near the village of Chmeľnica – eastern sector of the Pieniny Klippen Belt – PKB (the Inner Western Carpathians – IWC). The results of paleopiezometric investigations on deformed calcite veins from the PKB at Chmeľmica village within ductile deformed host rocks representing numeric data about the differential stresses from the final stages of ductile deformation of the calcite veins, penetrating the whole volume of host rocks. The number of deformation twins per 1 mm of the perpendicular diameter of the grain (D=31-52) at the grain-size (450.5-516 µm) has been produced by the recrystallization at differential stresses σ = 203.48-228.44 MPa.

The new results are given for comparison with previous ones, related with subducted and consequently exhumed rock blocks belonging to Jurassic Mélange proven from the southern Northern Calcareous Alps (NCA) – Hallstatt and Tirolic unit in the Eastern Alps (EA) (184.15–233.88 MPa) and the Meliatic Unit from the frontal parts of the Bôrka nappe, thrusted over the Gemeric Supernit in the IWC (347.49–439.55 MPa). Both measured units are representing the parts of the Jurassic Neotethyan Belt, striking from the Carpathians to the Hellenides.

The difference between differential stresses simultaneously indicates that the total dynamic recrystallization of allochthonous marbles from the Kurtová skala hill should occur in conditions of the subduction zone, but their post-exhumation transport on autochthonous carbonates without their whole-volume plastic deformation should occur in "could conditions" corresponding with the transport of the superficial nappe. The high differential stresses caused the origin of deformation twins nearly in each calcite grain (Twinning Incidence up to 100 %), as well as the high no. of deformation twins per 1 mm of the perpendicular diameter of the grain (D = 173.0 –646.25) was developed to the very small size of grains (23.7–42.7 µm). These results of differential stresses represent the highest values until found in the Inner Western Carpathians. The numeric paleopiezometric data obtained from the eastern sector of the PKB, as well as from the area of Pailwand, were measured in ductile deformed calcite veins, manifest the pressure conditions tightly before the "frozing" of the ductile deformation state at the final stage of thedeformation process. That mirrors not only in the markedly lower values of differential stresses, but also in the grain sizes of thin-sections within calcite veins from the PKB – the IWC (450.5–516 µm), as well as from the oceanic fragments of the Pailwand, the NCA, the EA (323.38 – 571.25 µm), which are much coarser in comparison with grain sizes of thin-sections from Bôrka nappe (23.7 – 42.7 µm; but also 174.0 – 403.20 µm in the case of grains, which undergone the static recrystallization in the rear parts of the Bôrka nappe).

Based on all these measurements, the method of paleopiezometry seems to be a usable tool for determination of differential stresses, which contribute to reveal a geological and tectonic interpretation of geodynamic history.

Key words: *Gemeric Superunit, Pieniny Klippen Belt, Penninic suture zone, Meliata-Hallstatt Ocean, Jurassic Mélange, Meliatic fragments/relics, Bôrka nappe, differential stresses, paleopiezometry.*

Introduction

The tectonic history of the Western Carpathians is linked with the origin of several orogenic belts during the Late Paleozoic/Mesozoic to the Cenozoic Era. The complex convergent movements encompass multiple crustal shortening, as well as the closure of some oceanic domains. Besides the Late Paleozoic Variscan orogenic belt, there are two Mesozoic and Tertiary zones considered as oceanic sutures or collided fossil plate boundaries present in the Western Carpathians (e.g. Froitzheim et al., 2008 in Plašienka, 2012).

The first Mesozoic one relates to the Middle-Late Jurassic closure of the Neotethyan (Meliata-Hallstatt) Ocean and its elements, known as the Jurassic Mélange (e.g. Krystyn & Lein in Haas et al., 1995). Typical examples of the Jurassic Mélange are the Hallstatt Mélange in the Northern Calcareous Alps (Frisch & Gawlick, 2003) and the Meliata Mélange in the Western Carpathians including the Bôrka nappe (Mello et al., 1998; Aubrecht et al., 2010). It consists of metamorphosed rocks, which are in the contact with prevailingly unmetamorphosed surrounding rocks (e.g. Gawlick et al., 1994; Gawlick & Höpfer, 1999; Missoni & Gawlick, 2011b). Similar complexes do not exist only in the southern Northern Calcareous Alps and in the Western Carpathians (Fig. 1), but also in the Dinarides, Albanides and Hellenides (Aubrecht et al., 2012). The need for reinvestigation of the Meliata Mélange aims to clarify the position of the Meliatic fragments within the Neotethyan Belt.

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The second one, the Pieniny Klippen Belt (PKB) represents a cca 600-700 km long trace of a major suture, representing the inner/outer Carpathian boundary (e.g. Andrusov, 1965; Scheibner, 1968; Maheľ, 1981; Birkenmajer, 1976a, 1986; Nemčok et al., 1998 in Jurewicz, 2005). The name of the PKB is related to the existence of two branches of Penninic Ocean, the South Penninic – Vahic Ocean and the North Penninic – Magura Ocean (Plašienka, 2003). The first stage of sea expansion and transgression within the PKB Basin took place in Anisian-Norian times (Birkenmajer, 1986, 1988; Birkenmajer et al., 1990) and was connected with the eastward lateral propagation of the Alpine Tethys rift (Dumont et al., 1996). The final ocean closure occurred no earlier than the Early Eocene (e.g. Neubauer, 1994; Oberhauser, 1991 in Ratschbacher et al., 2004).

The PKB is composed of the Jurassic, Cretaceous and Paleogene sediments. Due to a variable lithology and intricate structure, the PKB is considered as the most conspicuous regional zone of the Western Carpathians with typical klippen morphology, being a result of lithology and tectonic evolution (Plašienka, 1997). Two centuries of intense research divided the PKB into several lithostratigraphic and tectonic units of originally distant paleogeographic provenances. The majority of researches followed the general tectonic ideas, which were based on macroscopic structures indicated by field mapping, as well as the mutual relationship of rock units with known lithology and stratigraphic age (e.g. Andrusov, 1938, 1968; Birkenmajer, 1977 in Plašienka, 2012). Their grouping into lithostratigraphic and tectonic units have become a basis for all interpretations of the PKB structure and evolution. Recently, three principal tectonic units have been distinguished – Šariš Unit, Subpieniny Unit and Pieniny Unit (Plašienka & Mikuš 2010). They are ranged to the tectonic unit of higher order – the Oravic Superunit that represents the PKB "sensu stricto" (Plašienka 2012).

Despite the complicated tectonic history, the data about the thermal depositional history indicate that the PKB sediments were never buried to considerable depths and the deformation has occurred just in the brittle conditions.

Contrary to this, the rock blocks from the zone of Meliata-Hallstatt Ocean underwent the Jurassic tectonometamorphic evolution and were exhumed on the lower grade or unmetamorphosed sequences (Mello et al., 1997, 1998; Missoni & Gawlick, 2011b).

This paper aims to present new paleopiezometric results of the ductile deformed calcite veins from the eastern sector of the PKB – the Chmeľnica area and to compare them with earlier results, obtained from exhumed Meliatic blocks (Németh et al., 2012; Zákršmidová et al., in press).

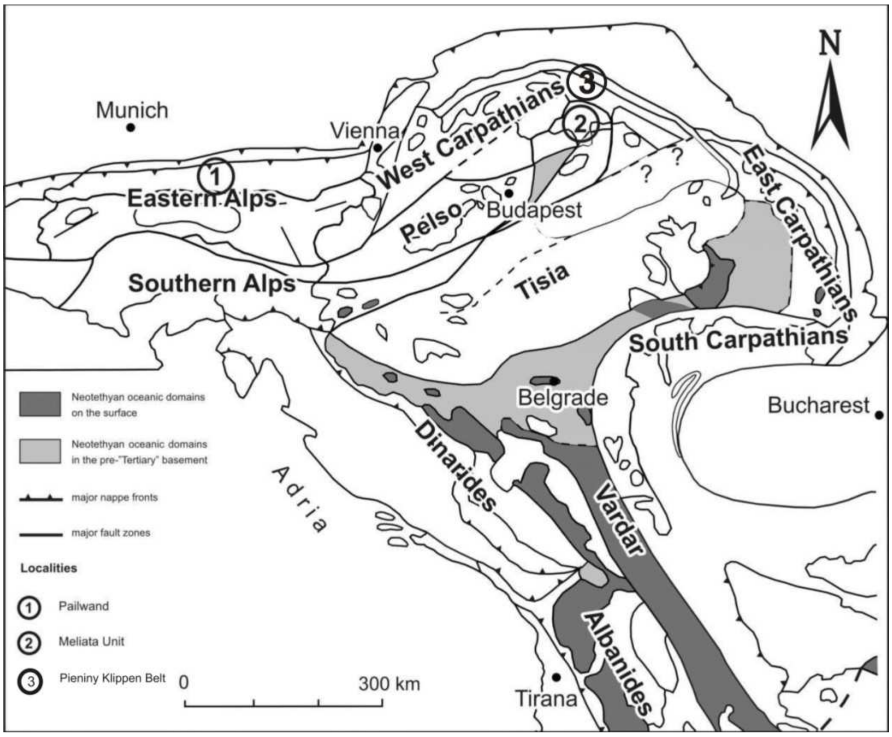

Fig. 1. Map of the Alpine, Carpathian, Dinaride, Albanide and Pannonian realm with the geographic distribution of Neotethyan oceanic crust and the tectonic position of studied samples. Map modified after Kovacs et al. (2010).

Methodology of paleopiezometry

The paleopiezometry, applied on recrystallized calcite grains either in the calcitic marbles or calcite veins, allows expressing the paleostresses numerically. The methodology of paleopiezometry is best calibrated for monomineralic calcite marbles, as well as quartzitic rocks with a pervasive ductile deformation (Rowe & Rutter 1990). At any transversal profile through the shear zone, or through the normal/reverse fault planes, the paleopiezometry allows revealing the changes in the deformation gradient.

Differential stresses ($\sigma_1 - \sigma_3$) in measured grains are in inverse relationship to sizes of measured grains. For the estimation of differential stress, respectively paleostress, there were used paleopiezometers (Mercier et al., 1977; Etheridge and Wilkie, 1981; Christie and Ord, 1980; Schmid et al., 1980; Michibayashi, 1993; Post and Tullis, 1999; Passchier and Trouw, 1996). There are known two independent methodologies of paleopiezometry: Quartz paleopiezometry and calcite paleopiezometry.

Quartz paleopiezometry takes into account only the size of dynamically recrystallized grains, what caused a large diversities in calibrations of different authors (Koch, 1983; Twiss, 1977; Mercier et al., 1977). It results in restriction of this methodology in the practical use (Németh, 2001, 2005).

Calcite paleopiezometry takes into account the size of dynamically recrystallized grains, but also the number and character of deformation twins. There are known two independent ways how to determine the differential stresses in calcitic rocks with the possibility of mutual comparison of their results. These methods are Twinning Incidence and Twin Density (Rowe & Rutter 1990).

Twinning incidence, I_t, is defined as a percentage of grains of the distinguished size interval that demonstrate microscopically visible twins. The differential stress σ ($\sigma_1 - \sigma_3$; MPa) can be distinguished by the therein stated equation, where *d* represents the size of grains in μm. The standard error in this technique, as stated by Rowe & Rutter (1990), is up to 31 MPa.

$$\sigma = 523 + 2.13\, I_t - 204 \log d \text{ [MPa]}$$

Twin density, *D*, is defined as the number of twins regarding the grain diameter, measured perpendicularly to the twins. Input data are necessary to be correlated with the variation coefficient 0.25 (Ranalli, 1984). The standard error of this method is 43 MPa. The relation of the differential stress on twin density *D* is as follows:

$$\sigma = -52.0 + 171.1 \log D \text{ [MPa]}$$

The primary data were obtained from thin sections, measuring the grain size in μm and number of deformation twins in corresponding grains. To guarantee the maximum representativeness of data, measurements were done systematically on profiles through the thin section taking into account each neighbouring grain. Extreme dimensions (extremely small or large grains) were excluded from following calculations, using the variation coefficient 0.25.

For numerical processing, a procedure consisting of several steps was developed (c.f. Németh, 2005):

1. Separation and batching of obtained data according to the grain size. This procedure is easier when working with relative values of the grain size, i.e. the number of segments on the micrometric scale. Determination of the real grain size in μm was obtained by multiplication of segments number by the real dimension of the segment in μm.
2. The finding of a number of grains in individual size categories as well as the grains with twins. Values are used for calculation of twinning incidence I_t.
3. Determination of the number of twins in individual size categories and sums of all perpendicular diameters of grains related to twins. Values are used for calculation of twin density D.

For the maximal correctness of obtained results, the calculation has been realized in six ways. Four calculations were restricted with the variation coefficient below 0.25 (+/- 25 %; Ranalli, 1984). By this way, we avoided inaccuracy of results by extremely small and large grains being included into the calculation.

Multiple determination of the differential stress by the method of Twinning Incidence:

1. The differential stress has been calculated selectively for each grain size class. The total differential stress has been calculated by weighted mean. The variation coefficient was not implemented into calculations.

2. The calculation of the total twinning incidence (without selective calculation for each grain size). Calculation with the coefficient of variation.

3. Determination of differential stress by the arithmetic mean from the partial results for individual categories. Calculation with the coefficient of variation.

4. Determination of differential stress by the weighted mean from the partial results for individual categories. Calculation with the coefficient of variation.

Multiple determination of the differential stress by method of Twin Density:

1. Calculation with the application of mathematically determined twin number with respect to grain sizes perpendicular to twins without separation of calculation for individual size classes. The coefficient of variation was not implemented into the calculation.

2. The same way of calculation with implemented coefficient of variation.

In a prevailing number of samples, the results of both methods (Twinning Incidence and Twin Density), were comparable. In several cases, we have registered some differential stresses. These will be discussed when commenting individual samples. The Twin Density Method is considered to be more precise, and obtained results (with the implementation of the coefficient of variation by Ranalli, 1984) seem to be more realistic.

Method implication

Penninic suture zone

The ductile eastern sector of the PKB – Chmeľnica

According to early realized structural researches, the entire deformation of the PKB units virtually occurred at very low temperatures at diagenetic conditions, which are dominated by brittle structures – faults, joints, syntectonic veins, etc., partially preceded or accompanied by a diffusion mass transfer mechanism, like the pressure solution and precipitation (Plašienka, 2012).

In the eastern section of the PKB, near the village of Chmeľnica, the intricate, i.e. closed and isoclinal folds were developed, being composed of the gray marly limestones with abundant occurrences of cherty limestones of Jurassic-Early Cretaceous age. A system of dislocations penetrates these rocks with the east-western strike, filled with 5–15 cm thick calcite material. The calcite veins, penetrating the ductile deformed host rocks, were analyzed microscopically, using the paleopiezometry method.

Taking into account the grain-size and the number of deformation twins, we measured 240 calcite grains in each studied thin-section. The representative grain-sizes in studied thin-sections – 450.5-516 µm and the 31-52 number of twins per 1 mm of perpendicular diameter revealed the differential stresses 203.48-228.44 MPa, which manifest the pressure conditions tightly before the "frozing" of the ductile deformation state at the final stage of deformation process (see Tab. 1, Fig. 2, 3).

The deformation twins at studied thin-sections are not the only microscopically observable indicator of the ductile deformation. In the calcite grains, we have revealed: *BLG* – Boulging, *SGR* – Subgrain Rotation and *GBM* – Grain Boundary Migration, which are followed by the onset of static recrystalization, accompanied with polygonization of grains (Passchier & Trouw, 1996).

Meliata-Hallsttat suture zone

Oceanic fragments from the frontal part of the Bôrka nappe (northward from the Jaklovce village) over thrusting the Gemeric Superunit (the Inner Western Carpathians – IWC)

The studied area was located in the apical part of the Kurtová skala hill, northward from the Jaklovce village. The thin-sections encompassed five calcitic marbles with strong recrystallization and one sample, taken on the eastern slope of the hill, showing with a weak tectonometamorphic overprint. Using the paleopiezometry method, we determined the differential stresses, involving 240 grains in each sample (Németh et al., 2012).

The stress field caused the recrystallization of the whole volume of calcite marbles, manifested by twins nearly in each calcite grain (Twinning Incidence up to 100 %). The high number of deformation twins per 1 mm of the perpendicular diameter of the grain (D=173.05–646.25) at the very small size of grains (23.7–42.7 μm) was caused by their recrystallization at high differential stresses σ = 347.49–429.55 MPa (see Tab. 2, Fig. 2, 3). In the case of the Kurtová skala hill, the paleopiezometric measurements have proved the allochthonous position of the limestones, being a part of the exhumed and translated Bôrka nappe of Meliaticum (Németh et al., 2012). The sample taken from the footwall autochthonous body does not exhibit deformation twins and ductile overprint.

Oceanic fragments from the Pailwand – the Northern Calcareous Alps (NCA), the Eastern Alps

The paleopiezometric measurements in the Pailwand (NCA) were applied to calcite veins penetrating the exhumed Hallstatt limestones. We followed the researches done by Gawlick & Königshof 1993; Gawlick & Höpfer 1999, Frank & Schlager 2006, which revealed the LT-HP tectonometamorphic overprint in exhumed sequence. Paleopiezometric measurements were applied to calcite veins penetrating the whole volume of the host rocks. In each thin section were measured 240 calcite grains. Obtained differential stresses (184.15 – 233.88

MPa, Fig.2, 3) indicate the pressure conditions during the final stages of exhumation of the host rock (Zákršmidová et al., in press).

Tab. 1. Twinning Incidence (It); Twin Density (D) and calculated pressure conditions of the calcite veins from the eastern sector of the PKB – Chmeľnica village.

		Twinning Incidence (I_t)					Twin Density (D)		
	Representative grain – size	Calcul. without variation coef.	It for interval determined by variation coefficient	Calculation with variation coefficient			D – no. of twins per 1 mm of perpend. diameter	Calculat. without variation coeffic.	Calculat. with variation coeffic.
		Calculat. with weight. mean		Calculat. with the whole It	Arith. mean of σ for size interval classes	Weight. mean of σ for size classes			
	µm	σ(MPa)		σ(MPa)	σ(MPa)	σ(MPa)		σ(MPa)	σ(MPa)
PKB-3a	516	119.46	66	110.27	124.42	119.46	31	199.40	**203.48**
PKB-3b	450.5	201.97	36	199.78	226.2	201.97	52	242.6	**240.44**

Tab. 2. Twinning Incidence (It) and Twin Density (D) and calculated pressure conditions of the studied samples from the Kurtová skala hill (frontal part of the Bôrka nappe) – "Jaklovce Meliaticum"- relics of the Meliata-Hallstatt Ocean/Meliatic Unit thrust over the Gemeric Superunit. The laboratory paleopiezometry and computing done by Zákršmidová (2012) in Németh et al. (2012).

		Twinning Incidence (I_t)					Twin Density (D)		
	Representative grain – size	Calcul. without variation coef.	It for interval determined by variation coefficient	Calculation with variation coefficient			D – no. of twins per 1 mm of perpend. diameter	Calculat. without variation coeffic.	Calculat. with variation coeffic.
		Calculat. with weight. mean		Calculat. with the whole It	Arith. mean of σ for size interval classes	Weight. mean of σ for size classes			
	µm	σ(MPa)		σ(MPa)	σ(MPa)	σ(MPa)		σ(MPa)	σ(MPa)
Autochthonous sequences of Jaklovce Meliaticum									
JAK-4	18.5	*No deformation lamellae are present in autochthonous limestone*							
Allochthonous sequences of Jaklovce Meliaticum									
JAK-5	23.7	269.40	12.22	268.72	272.07	269.40	173.05	330.95	**347.49**
JAK-7	27.7	356.45	59.52	355.62	353.29	281.27	355.32	384.41	**386.44**
JAK-46	40.6	411.63	100	407.79	405.79	408.52	487.61	407.93	**406.73**
JAK-48	58.2	208.46	99.29	374.42	373.43	375.30	381.59	389.71	**389.37**
JAK-54	42.7	407.15	100	403.40	403.73	404.25	646.41	428.88	**429.55**

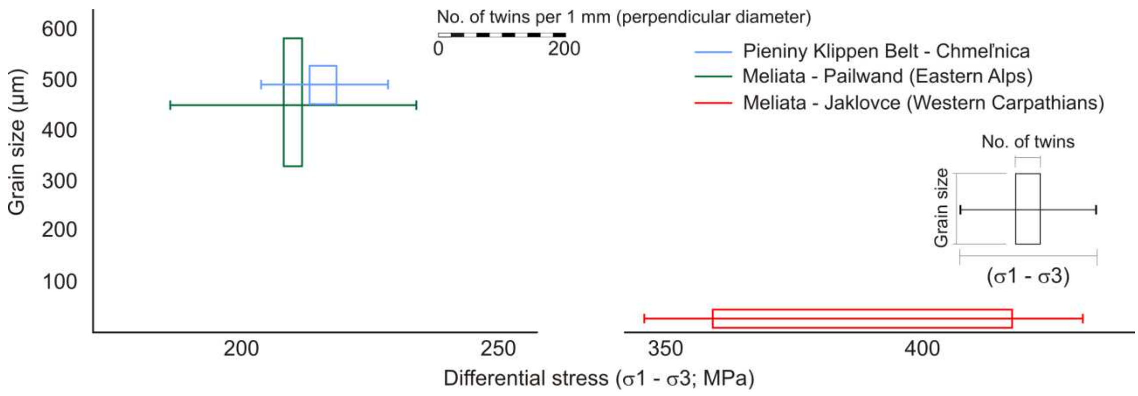

Fig. 2. Graph of the relationship between the paleopiezometrically measured differential stresses (σ_1 - σ_3), grain sizes and deformation twins. In general, lowering of grain sizes caused increasing of differential stresses (these parameters are in an inverse relationship), whereas the number of deformation twins increases proportionally with the increasing differential stresses.

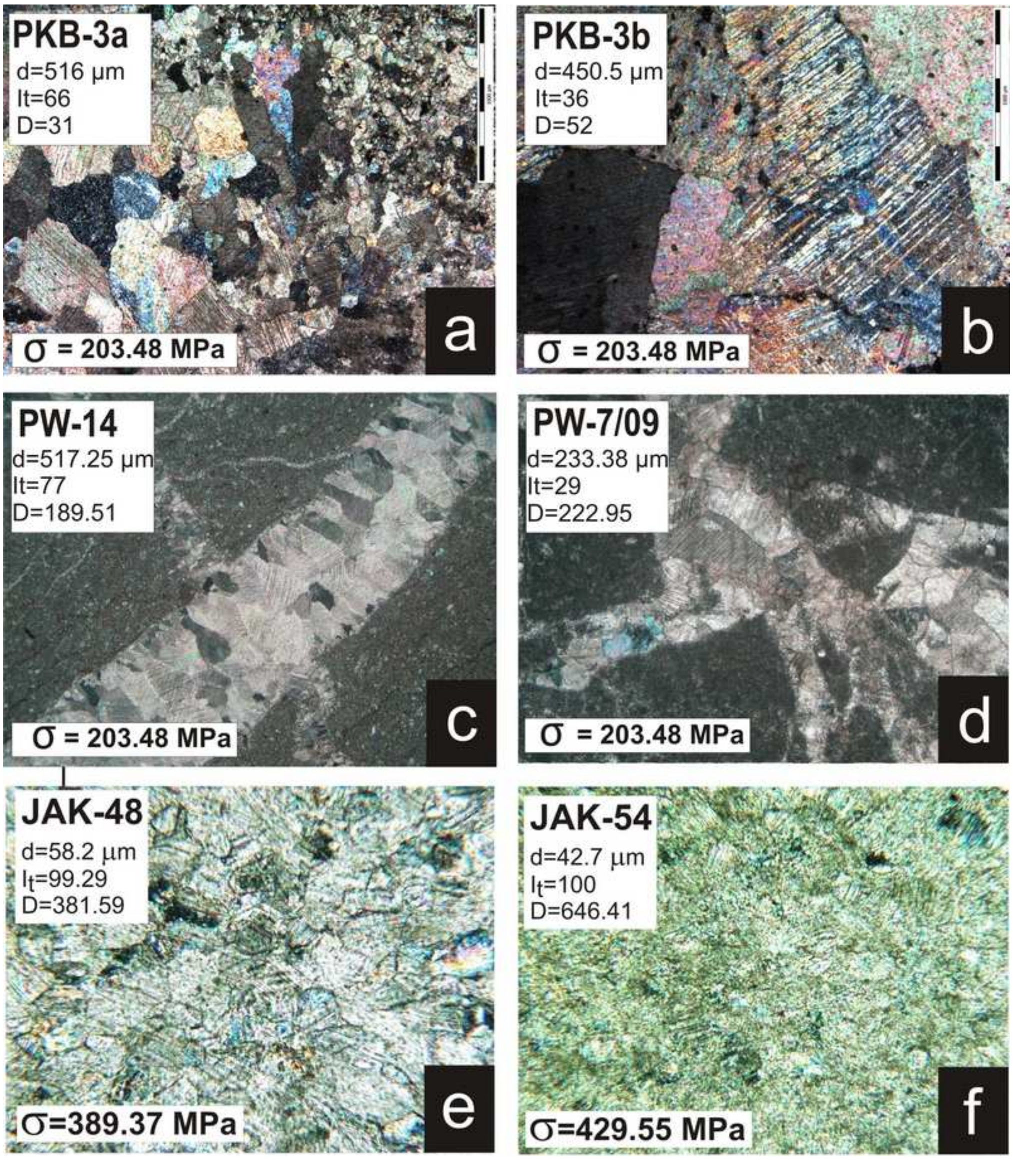

Fig. 3. Microphotographs with following parameters: d – average grain-size, It - Twinning Incidence – the percentage of grains with deformation twins; D – Twin density – the average number of twins per 1 mm of the perpendicular diameter of the grain; σ – differential stress MPa.

A) B) Microphotographs of studied samples of calcite vein from the Chmeľnica area (eastern sector of the PKB)

C), D) Microphotographs of studied samples of calcite vein from the Pailwand area – the NCA (the EA) in Zákršmidová et al. (in press).

E), F) Microphotographs of studied samples of marbles from the apical part of the Bôrka nappe thrusted over the Gemeric Supernit (the IWC) in Németh et al. (2012).

Discussion

The first paleopiezometric investigations of exhumed Bôrka nappe calcitic marbles (Németh in 2001, 2005, Németh et al., 2012) have proved the allochthonous position of these Jurassic Mélange fragments of Meliatic Unit, thrusted over the Western Carpathian Gemeric Superunit. In frontal parts of the displaced Bôrka nappe, the differential stresses reached 439.55÷347.49 MPa, while in the rear parts stress reached markedly lower values, i.e. 277.92÷187.56 MPa (Németh, 2005; Németh et al., 2012). The lower values of the differential stress of rear parts of the nappe reveal a consequence of ongoing static (post-dynamic) recrystallization in the still warm rear part of the nappe, buried in the upper levels of the subduction/exhumation zone. The frontal parts of the nappe at that time were already displaced by the kinematics of superficial nappe, having "frozen" earlier higher differential stresses from the subduction/exhumation zone. The results coincide with revealed nappe position, P-T conditions and exhumation kinematics of the Bôrka nappe outliers confirmed by other authors (Mello et al., 1997, 1998; Ivan, 2002; Ivan et al., 2009; Ivan & Méres, 2009; Putiš et al., 2011, 2012).

Besides the above stated differential stresses, revealed for the Bôrka nappe of Meliatic Unit, there are also available the values of differential stresses from both the Lower Paleozoic sequences of Gemeric Superunit related to Variscan tectogenesis and the values from the contact zone of Gemeric and Veporic units, related to Alpine deformation of this zone (Németh, 2005). All the mentioned results were obtained by the same methodology.

In the Pailwand of the Eastern Alps, the exact numeric paleopiezometric data were supplemented by the results of the Conodont Alteration Index (CAI), the Calcite-dolomite solvus thermometry in Gawlick & Königshof (1993); Gawlick & Höpfer (1999), the age ($^{40}Ar/^{39}Ar$) data in Frank & Schlager (2006) and by the phengite barometry in Gawlick & Höpfer (1999). All these data provide information about temperature and pressure conditions during the prograde, resp. retrograde metamorphism.

According to previous structural researches, the entire deformation of the PKB units virtually occurred at very low temperatures at diagenetic conditions, which is accompanied by brittle structures, followed by the diffusion mass transfer mechanism, such as pressure solution and precipitation (Plašienka, 2012). The intricate structure of the PKB exhibits the manifestation of brittle, as well as ductile deformation due to polyphase tectonic evolution (Nemčok & Nemčok, 1994; Jurewicz, 2005; Plašienka and Mikuš, 2010; Plašienka, 2012), in which four main deformation stages D1–D4 were identified (Plašienka, 2012).

Within the studied area, at the eastern sector of the PKB, near the Chmeľnica village our paleopiezometric research reveals differential stresses 203.48–228.44 MPa, which are comparable (Fig. 2) with those attested in other regional ductile domains (cf. Németh, 2005; Németh et al., 2012, Zákršmidová et al., in print). The oceanic fragments of the Pailwand – the Northern Calcareous Alps (NCA), the Eastern Alps (EA) (184.15–233.88 MPa), as well as the Bôrka nappe – the Inner Western Carpathians (IWC) (347.49–439.55 MPa) belong to them. The grain sizes of thin-sections within calcite veins from the PKB – the IWC (450.5–516 µm), as well as from the oceanic fragments of the Pailwand – the NCA, the EA (323.38–571.25 µm) are much coarser in comparison with grain sizes of thin-sections from the Bôrka nappe (23.7–42.7 µm; but also 174.0–403.20 µm in the case of the grains which have undergone static recrystallization, cf. Németh, 2005).

Twins are not the only microscopically visible indicator of ductile deformation. In studied thin-sections are preserved others, e.g.: *BLG* – Boulging, *SGR* – Subgrain Rotation and *GBM* – Grain Boundary Migration – the precursor of the onset of static recrystallization (Passchier and Trouw, 1996).

Furthermore, we need to emphasize that the differential stresses (σ_1 - σ_3) in newly formed fractures are in both cases, (i.e. at the PKB and at the NCA – the EA) filled with calcite cement, which nevertheless underwent minor ductile deformation and preserved the P-T conditions at the final stage of deformation. Obtained differential stresses registered in calcite veins likely reflect the total stress field effecting on the whole rock sequence tightly before decreasing temperature had "frozen" the parameters of the ductile deformation.

Taken into consideration results of studied localities (cf. Fig. 1), we identified within studied outcrops two deformational subphases of ductile deformation. The first one relates to ductile deformation of host rocks. The decrease in temperature caused the change of ductile régime of host rock to brittle-ductile, or even brittle, and the origin of fractures, being infilled with calcite from migrating fluid. The second subphase reflects a ductile recrystallization of the calcite veins, without the deformation of the host rocks.

Conclusions

The paleopiezometric measurements in the eastern part of the PKB indicated the poly-stage tectonic evolution. Calcite veins generated within the studied folds, penetrate the whole volume of the host rock. The ductile deformation of the calcite veins, revealed by the number of deformation twins per 1 mm of perpendicular grain diameter (D = 31–52) at the grain-size (450.5–516 µm) has been produced by the recrystallization at differential stresses σ = 203.48–228.44 MPa. Further indicators observed in the veins in the microscopic scale (*BLG* – Boulging, *SGR* – Subgrain Rotation, *GBM* – Grain Boundary Migration) prove the ductile character of deformation. Based on the fact from the previous researches, the calcite veins are able to preserve information about differential stresses from the final stages of deformation processes.

Taking into consideration all paleopiezometric results, obtained by applied methodology, we conclude that the paleopiezometry in combination with other structural/microstructural methods is usable for determination of stress conditions in the ductile zones, in either ductile deformed calcite marbles as host rocks, or in ductile deformed calcite veins, penetrating host rocks, and represents a relatively sensible methodology for calculation of differential stresses.

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