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Paleopiezometry: Tool for determination of differential stresses for principal ductile shear zones of Gemericum, Western Carpathians

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Abstract. In contribution the differential stresses during dynamic recrystallization of monomineralic rocks (quartzites, calcitic marbles) are numerically expressed using paleopiezometry.

Research took into account comparable protoliths from the main ductile shear zones in Gemeric region. The deformation gradients during Alpine collisional imbrication (AD_1; calcitic marbles of Lower Paleozoic Holec Beds of Gemeric Gelnica Group) and Bôrka nappe displacement (southern and northern occurrences; AD_1) as well as the post-collisional unroofing (AD_2) in the eastern contact zone of Gemericum with Veporicum are documented.

The research contributed to methodology of calcite paleopiezometry (methods of Twinning Incidence and Twin Density) using altogether six ways of differential stress calculation and compared it with quartz paleopiezometry. The case comparison of both methodologies (calcite and quartz paleopiezometry) was realized on neighbouring marble and quartzite mylonite beds in the Črmeľ valley, documenting the ductile low angle normal faulting (unroofing) in the eastern contact zone between Gemericum and Veporicum (Margecany zone; AD_2 phase).

Key words: paleopiezometry, ductile shear zones, imbrication, unroofing, Bôrka nappe, Gemericum, Veporicum.

Introduction

Previous study (Németh, 2001, 2002) has distinguished three ductile shear zones of principal importance in tectonic evolution in Gemeric region:

1. Shear zone between Lower Paleozoic Gelnica and Rakovec Groups (Variscan; linear course of E-W direction bended to NW-SE in its eastern segment; product of deformation phase VD; kinematics of south-vergent exhumation overthrusting of Rakovec Group melange on Gelnica Group; Figs. 1 and 3),

2. Bôrka nappe north-vergent displacement mylonitic horizons (Alpine; areally outcropping nappe outliers; deformation phase AD_1; exhumed melange of Meliata-Hallstatt basin marginal facies) and

3. Shear zone between Gemericum and Veporicum (Alpine; linear bended course separating both megaunits corresponding with Lubeník-Margecany line; pervasive ductile deformation during AD_2 phase; Alpine post-collisional unroofing of SE- and SW-vergency in western resp. eastern part of the contact zone).

The main aim of the paleopiezometry application was the obtaining of the exact numeric data about the distribution of differential stresses in mylonites of comparable protoliths and thus to contribute to reconstruction of geodynamic evolution. The paleopiezometry is best calibrated for monomineralic calcitic and quartzy rocks (marbles, quartzites), so our attempt was to collect samples with evident ductile deformation from the most softened parts of the shear zones listed above.

The softest horizon, where the south-vergent ductile shear zone between Gelnica and Rakovec Groups has developed (exhumation kinematics; designation 1 in Fig. 1), consists of green and grey laminated flyschoid sandstones, green metapelites, acid and intermediate volcaniclastics and basalt pyroclastics. Because no suitable monomineralic tectonites were found directly in the shear zone, our research took into consideration the Lower Paleozoic calcitic marbles from Holec altitude point and from Gočovo village (Holec Beds, Betliar Formation, central part of Gemericum; Figs. 1 and 3). As discussed later, because of the position of this marble strip at the base of the north-vergent Alpine AD_1 overthrust (Fig. 3) we suppose that the preserved ductile deformation in studied marbles was more realistically caused by AD_1 overthrusting than by Variscan VD phase.

The evidences of two phase deformation of these marbles were not found. It confirms former interpretation (Németh, 2002), that during the south-vergent VD exhumation the lowermost horizons of Lower Paleozoic rock pile were protected against deformation by their position near the rigid crystalline basement, and the deformation was accommodated by the uppermost horizons of autochthonous Gelnica Group. As shown further in the text, the results of paleopiezometry brought new data for this assumption.

The calcite paleopiezometry applied on southern and northern occurrences of the Bôrka nappe (designed 2 in Fig. 1) aimed to contribute with new data to prolonged discussion about one or two branches of Meliata ocean, resp. autochthonous or allochthonous position of the Jaklovce Meliaticum. Studied samples were represented with the coarse-crystalline and multitwins calcitic marbles from Šugov valley, Špičiak hill and Zádiel valley

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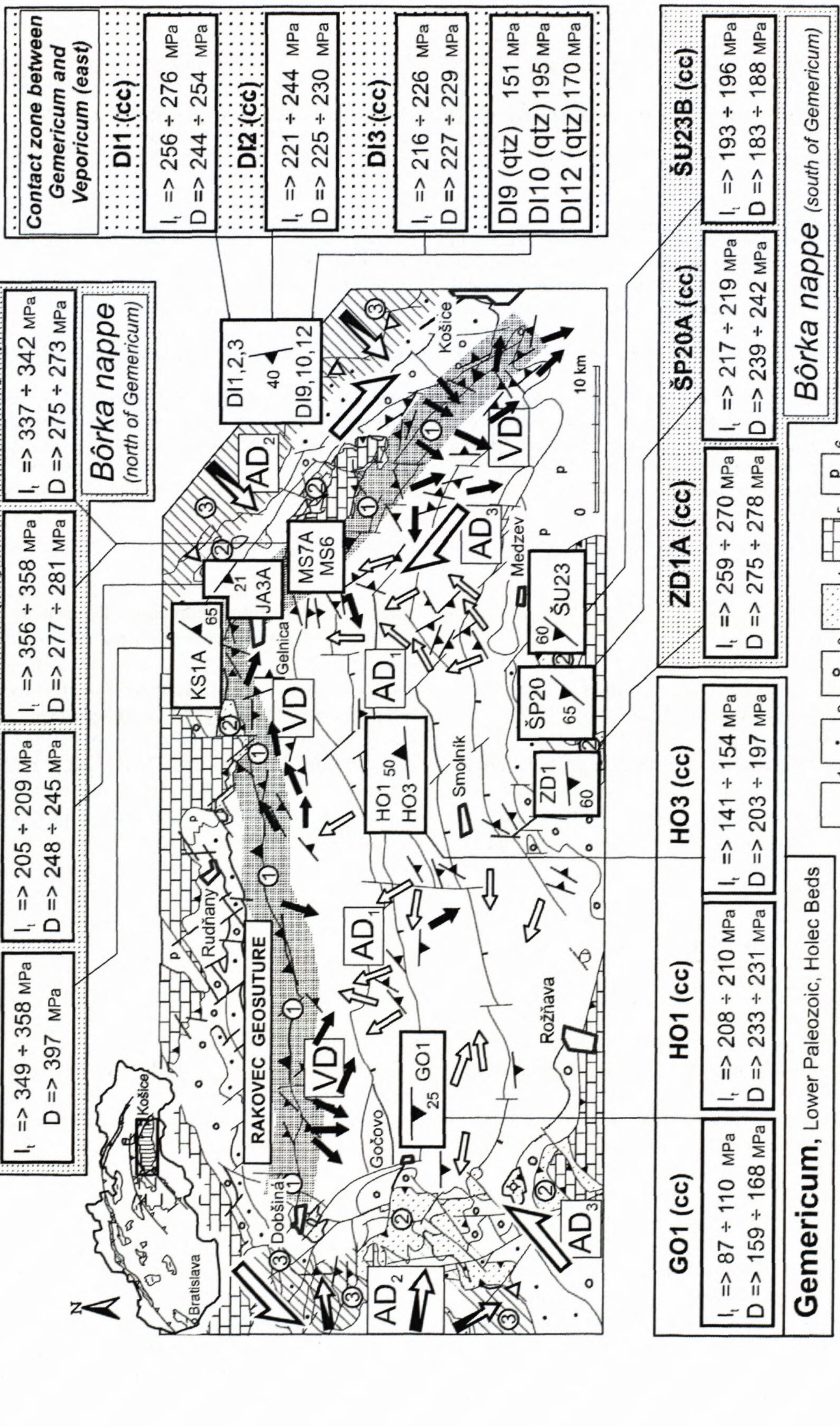

KS1A (cc)
I_t => 349 ÷ 358 MPa
D => 397 MPa
JA3A (cc)
I_t => 205 ÷ 209 MPa
D => 248 ÷ 245 MPa
MS6 (cc)
I_t => 356 ÷ 358 MPa
D => 277 ÷ 281 MPa
MS7A (cc)
I_t => 337 ÷ 342 MPa
D => 275 ÷ 273 MPa
Bôrka nappe
(north of Gemericum)
Contact zone between Gemericum and Veporicum (east)
DI1 (cc)
I_t => 256 ÷ 276 MPa
D => 244 ÷ 254 MPa
DI2 (cc)
I_t => 221 ÷ 244 MPa
D => 225 ÷ 230 MPa
DI3 (cc)
I_t => 216 ÷ 226 MPa
D => 227 ÷ 229 MPa
DI9 (qtz) 151 MPa
DI10 (qtz) 195 MPa
DI12 (qtz) 170 MPa
RAKOVEC GEOSUTURE
Bratislava
Košice
Dobšiná
Gočovo
Rudňany
Gelnica
Smolník
Rožňava
Medzev
VD
AD1
AD2
AD3
GO1
HO1
HO3
KS1A
JA3A
MS7A
MS6
DI1,2,3
DI9,10,12
ZD1
ŠP20
ŠU23
10 km
GO1 (cc)
I_t => 87 ÷ 110 MPa
D => 159 ÷ 168 MPa
HO1 (cc)
I_t => 208 ÷ 210 MPa
D => 233 ÷ 231 MPa
HO3 (cc)
I_t => 141 ÷ 154 MPa
D => 203 ÷ 197 MPa
ZD1A (cc)
I_t => 259 ÷ 270 MPa
D => 275 ÷ 278 MPa
ŠP20A (cc)
I_t => 217 ÷ 219 MPa
D => 239 ÷ 242 MPa
ŠU23B (cc)
I_t => 193 ÷ 196 MPa
D => 183 ÷ 188 MPa
Bôrka nappe (south of Gemericum)
Gemericum, Lower Paleozoic, Holec Beds

(southern occurrences of the Bôrka nappe) as well as Kurtová and Murovaná skala hills and Jaklovce village (Jaklovce Meliaticum/?northern occurrences of the Bôrka nappe).In the ductile shear zone, representing the eastern contact zone between Gemericum and Veporicum (Margecany line; AD_2; designation 3 in Fig. 1), the case comparison of both methodologies (calcite and quartz paleopiezometry) was realized on neighbouring marbles and quartzites at Diana locality in the Črmeľ valley.

Methodology

The size of dynamically recrystallized grains in deformed rock relates on differential stress. This principle was used in paleopiezometers for estimation of paleostress (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 and others). The paleopiezometry was best elaborated for monomineralic rocks with pervasive ductile deformation - calcitic marbles and quartzites.

Quartz paleopiezometry. This method takes into consideration only one parameter - the size of dynamically recrystallized grains. This is the reason of large diversities in calibrations of different authors (Koch, 1983; Twiss, 1977; Mercier et al., 1977) resulting to restriction of this methodology in practical use. This inappropriateness is demonstrated in Fig. 2, documenting the calibrations used for the earlier obtained results from the locality Košice – Diana (Németh and Putiš, 1999).

Calcite paleopiezometry. Because of the weakness of quartz paleopiezometry, the accent in our study has been given for calcite paleopiezometry, accounting the size of dynamically recrystallized calcite grains, but also the number and character of deformation twins. Moreover, there are known two independent ways how to determine the differential stresses in calcitic rocks with the possibility of mutual comparison of results of both methods. These methods are *Twinning Incidence* and *Twin Density* (Rowe and Rutter, 1990).

Twinning incidence. It, is defined as the percentage of grains of the distinguished size interval that demonstrate optically visible twins. We have measured in each sample 240 grains. The differential stress σ(MPa) was determined using below stated equation, where d represents the size of grains in µm (sensu l.c.). The standard error in this technique was stated by its authors 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 by the variation coefficient 0.25 (Ranalli, 1984). The standard error in this method is 43 MPa. The differential stress relates on twin density D by the following equation:

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

The primary data were obtained from thin sections, measuring the grain size in µm and number of deformation twins in corresponding grain. To guarantee the maximum representativeness of data, measurements were done systematically on profiles through 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 we developed the below described procedure, consisting from several steps:

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 micrometric scale. Determination of the real grain size in µm was obtained by multiplication of segments number by the real dimension of segment in µm.

2. Finding of number of grains in individual size categories as well as the grains with twins. Values are used for calculation of twinning incidence It.

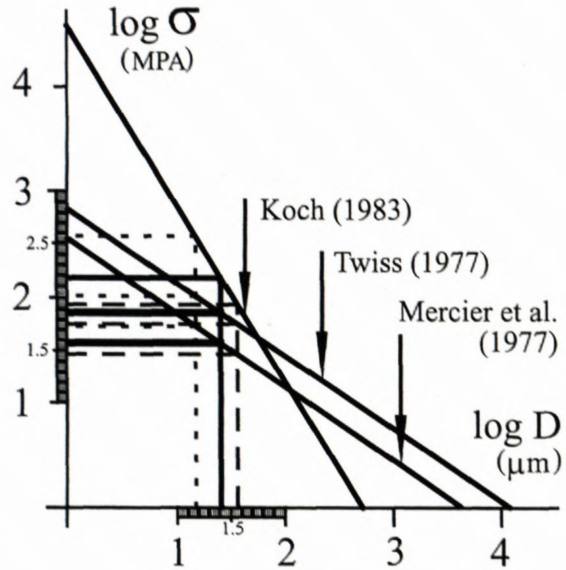
3. Determination of the number of twins in individual size categories and sums of all perpendicular diameters of grains related to twins. Obtained information was used for calculation of twin density D.

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

Fig. 1. Location of studied samples and results of paleopiezometry in Gemeric region. Lithology: 1 – Lower Paleozoic rocks of Gemericum, 2 – Carboniferous rocks of Gemericum and in its contact with Veporicum, 3 – Permian rocks of Gemericum, 4 – Upper Paleozoic and Triassic rocks of Meliaticum (Bôrka nappe), 5 – Mesozoic rocks of Silicicum, 6 – Paleogene. Numbers in circles designate the principal ductile shear zones: 1 – s.z. between Gelnica and Rakovec Groups (Variscan obduction kinematics; thick dotted line), 2 – Bôrka nappe (exhumed and obducted Meliaticum), 3 – s.z. between Gemericum and Veporicum (Alpine overthrust and subsequent unroofing). Arrows indicate kinematics during Variscan obduction and collision VD (black arrows) and Alpine tectogenesis (AD_1 – white arrows; AD_2 – half filled arrows; AD_3 – half-arrows). Location of samples: Lower Paleozoic Holec Beds of Gemericum: GO1 – Gočovo village, unnamed hill 1.5 km to SSE of the village, HO1 and HO3 – Holec altitude point 6 km to NE of Smolník village. Outliers of Bôrka nappe in Southern Gemericum: ŠU23B – Šugov valley 4 km to SSW of Medzev town, ŠP20 – Špičák altitude point (808 m) 4 km to WSW of Medzev town, ZD1 – Zádiel valley 11 km SE of Smolník town. Outliers of Bôrka nappe in Northern Gemericum: KS1A – 1.5 km to NNW of Jaklovce village, JA3A – 1.2 km to NE of Jaklovce village, MS6 and MS7 – 1.5 km to NE of Kojšov village. Eastern contact zone between Gemericum and Veporicum: DI1, DI2, DI3, DI9, DI10, DI12 – Črmeľ valley, Diana hunter hut 3.5 km to NW of Kavečany village near Košice.

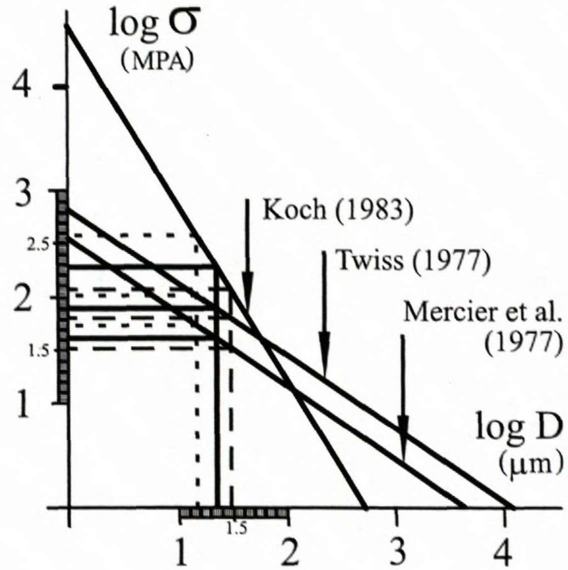
DI9 (qtz)

σ (MPA)		Koch (1983)	Twiss (1977)	Mercier et al. (1977)
aver. diam	——	151.3	75.9	38.0
max. diam	– –	89.1	57.5	29.5
min. diam	- - -	371.5	102.3	55.0



DI10 (qtz)

σ (MPA)		Koch (1983)	Twiss (1977)	Mercier et al. (1977)
aver. diam	——	195.0	83.2	42.7
max. diam	– –	120.2	64.6	32.4
min. diam	- - -	389.1	102.3	56.2



DI12 (qtz)

σ (MPA)		Koch (1983)	Twiss (1977)	Mercier et al. (1977)
aver. diam	——	169.8	83.2	43.7
max. diam	– –	104.7	64.6	31.6
min. diam	- - -	407.4	125.9	67.6

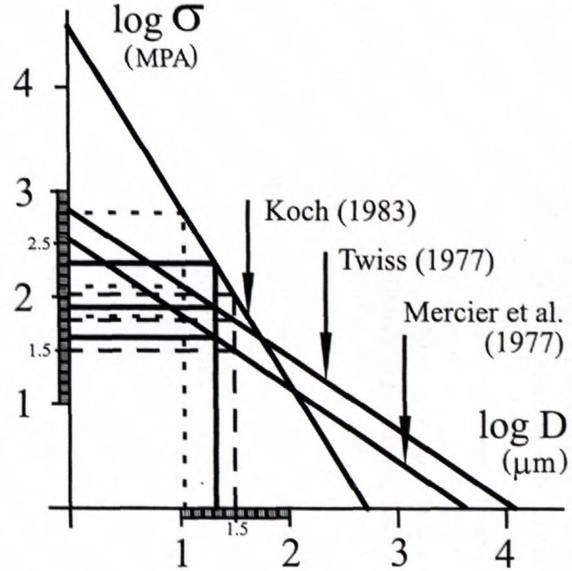


Fig. 2. Quartz paleopiezometry: Determination of differential stresses affecting during deformation AD_2 on Veporic cover quartzites (eastern contact zone of Gemericum and Veporicum) in the locality Košice-Diana. The quartzite bed (samples DI9, DI10, DI12) is in immediate vicinity of the bed of calcitic marbles (samples DI1, DI2 and DI3). Tables above graphs in figure display differing differential stresses obtained using calibrations by Koch (1983), Twiss (1977) and Mercier et al. (1977). Stresses were calculated in each calibration for minimal, maximal and average diameters of grains. The results were compared with results of calcite marbles paleopiezometry of samples DI1, DI2 and DI3, neighbouring to studied quartzites and suffering the comparable AD_2 overprint. Nearer to results of calcite paleopiezometry and geologically most significant are the results by Koch (1983) calibration when taking into account the average diameter of grains. These results indicate, that quartz bed represented either softer medium for stress accommodation and displacement than marble bed, or the marble bed accommodated majority of deformation being located closer to thrust plane.

Multiple determination of the differential stress by 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 with 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 application of mathematically determined twins number with respect to grain sizes perpendicular to twins without separation of calculations for individual size classes. The coefficient of variation was not implemented into calculations.

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

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

Obtained data

Lower Paleozoic calcitic marbles of Gelnica Group

To contribute for comprehensive characterization of the tectonic evolution of the Gemericum, we tried to obtain the deformation characteristics of comparable lithologies from individual shear zones. Because of the absence of suitable monomineralic lithology in ductile shear zone dividing Lower Paleozoic Rakovec and Gelnica Groups (VD phase of deformation), for characterization of the deformation gradient in Lower Paleozoic Gemeric sequences we studied carbonates from the deeper lithostratigraphic levels of the Gelnica Group (Lower Paleozoic Holec Beds of Betliar Formation; Fig. 3). The samples were taken directly from the Holec elevation point (804) in the centre of Gemericum (**HO1**, **HO3**) and ESE of the village Gočovo (**GO1**; Fig. 1).

Paleopiezometry of the less deformed calcitic marble found in the Gemeric region, **GO1** *(AS_2 = 180/25)*, demonstrated the lowest values of differential stress (87 ÷ 110 MPa by Twinning Incidence, T.i., and 159 ÷ 168 MPa by Twin Density, T.d.; compare data in Table 1). Calculated representative grain size is 253.90 μm. Differential stress caused migration of grain boundaries accompanied with origin of deformation twins in some grains.

The calcitic marble **HO1** *(AS_2 = 355/50)* consists of seriate interlobate calcite grains. Representative grain size is 202.90 μm. More intensive deformation of HO1 in comparison with HO3 is indicated also by higher values of differential stresses (208 ÷ 210 MPa contrary to 141 ÷ 154 MPa by T.i., and 233 ÷ 231 MPa contrary to 203 ÷ 197 MPa by T.d.) and results in origin of microshears.

Calcitic marble **HO3** *(AS_2 = 355/50)* represents type with distinctly elongated grains. The average grain-size is 350.80 μm. The trends to grain boundary area reduction in marble HO3 in comparison with HO1, are reflected also by the lower differential stresses. The comparison of data of samples **HO1** and **HO3** from different carbonatic lenses of Holec Beds suggests the role of the protolith character prior deformation (e.g. different granularity) as well as possibly slightly different deformation temperature of rocks recently outcropping in close vicinity.

Carbonates from the Bôrka nappe outliers in Southern and Northern Gemericum

Coarse-grained calcitic marbles represent several hundred metres thick bed in Dúbrava Fm. of Hačava Sequence (cf. Mello, ed., 1997). They form sceneric hills Jelení vrch (947) and Špičák (808) to WSW of the village Medzev. Carbonates often contain intercalations of basic pyroclastic material, after tectonization and boudinage being reshaped to σ and δ porphyroclasts (known excursion localities in termination of the Šugov valley). In microscale the thin calcitic intercalations are typical feature nearly for all lithotypes of Dúbrava Fm.

Coarse-grained marbles contain twins of several generations. Oldest generation of thick twins of low number (usually to 5) indicates higher temperature conditions of their origin. Inside big calcite grains (average dimensions 300-400 μm) are closed small quartz and albite grains. It indicates total recrystallization of carbonatic matter and resetting of original grain boundaries. With generation of twinning also the core-mantle structures in marbles are related. First system of twins is penetrated with younger system of very thin deformation twins of extremely high number (about 50 twins per grain are the common case). Successive decrease of temperature during generation of both systems is indicated by twinning character - first system has variegated twin thicknesses along their course and their bending is characteristic (temperature of origin of first system is above 200-250 °C). Younger system contain sharp, strait twins of razor-type (<200 °C). Anomalously high number of deformation twins of the second system indicates, that deformation has realized in the high state of plasticity with bulk distribution of differential stress in whole crystal lattice and activation of each suitable lattice plane. Described two twin systems are penetrated by brittle fractures being the result of final low T brittle deformation.

Paleopiezometry was applied on samples from the terminations of Šugov valley (**ŠU23B**; AS_2 = *340/60*), Zádiel valley (**ZD1A;** AS_2 = *175/60*) and from apical parts of the elevation point 808 m Špičák (**ŠP20**; AS_2 = *312/65*). The finding that described coarse-grained marbles do not ex-

Table 1 Results of paleopiezometry of calcitic marbles obtained by six ways of calculation by methods of Twinning Incidence and Twin density (location of samples – see explanation to Fig. 1).

		TWINNING INCIDENCE					TWIN DENSITY		
	Representative grain-size	Calcul. without variation coeffic.	It for interval determined by variation coefficient	Calculation with variation coefficient			D – number of lamellae per 1 mm of perpendicula diameter	Calculat. without variation coeffic.	Calculat. with variation coeffic.
		Calculat. with weight. mean		Calculat. with the whole It	Arith. mean of σ for size classes	Weight. mean of σ for size classes			
	µm	σ(MPa)		σ(MPa)	σ(MPa)	σ(MPa)		σ(MPa)	σ(MPa)
Lower Paleozoic carbonates of Holec Beds – AD_1 phase									
GO1	253.90	109.95	26.04	87.91	87.17	88.65	17.18	159.30	**168.06**
HO1	202.90	209.99	73.19	208.20	209.86	208.95	46.17	232.80	**230.98**
HO3	350.80	154.45	64.49	141.16	154.85	144.89	30.93	203.00	**197.39**
Bôrka nappe (outliers in Southern Gemericum) – AD_1 phase									
ŠU23B	403.20	193.09	95.08	193.99	195.74	195.02	23.77	183.40	**187.56**
ŠP20A	330.00	217.44	90.14	201.23	192.40	219.46	50.35	239.20	**242.12**
ZD1A	174.00	270.13	90.43	258.55	266.37	259.37	81.10	274.60	**277.92**
Bôrka nappe (outliers in Northern Gemericum) – AD_1 phase									
KS1A	58.08	358.31	88.64	351.93	348.92	352.93	420.3	396.90	**396.66**
JA3A	165.10	205.46	64.38	207.71	211.33	208.57	56.96	248.40	**244.79**
MS6	50.73	358.43	85.71	357.70	356.33	358.46	84.17	277.40	**281.46**
MS7	56.09	342.28	82.35	341.63	337.23	342.28	81.63	275.10	**273.03**
Ductile shear zone between Gemericum and Veporicum - AD_2 phase									
DI1	54.95	276.46	41.38	256.18	253.32	256.96	53.72	244.00	**253.71**
DI2	85.02	243.70	43.28	221.57	221.08	222.39	41.77	225.30	**230.13**
DI3	95.19	215.77	49.52	224.85	221.31	226.08	42.81	227.20	**228.82**

hibit considerable high differential stresses was surprising (183-278 MPa in the whole range of results; Tab. 1, Fig. 1). It is probable due to the fact that deformed material was coarse-grained already prior this pervasive deformation (**ŠU23B** 403.20 µm, **ŠP20** 330.00 µm, **ZD1A** 174.00 µm) and the grain size represents the principal parameter in mathematical expression in both calibrations.

From the Bôrka nappe outliers in Northern Gemericum (deformation phase AD_1) our research took into account the marbles from the lower carbonatic horizon of the north-western slope of the Murovaná skala massif south-east of Gelnica town (samples **MS6** and **MS7**) and those of so-called Jaklovce Meliaticum (**JA3A**, ENE of Gelnica town; AS_2 = *216/21*). As proved by microtectonic studies (Németh, 2001), thin section parallel with the dip of foliation indicated in Jaklovce sample tectonic transport top-to-the-NE. The carbonates from the North Gemeric Bôrka nappe outliers of the representative grain size 50.73-58.08 µm (**KS1A,** AS_2 = *125/65*; **MS6** and **MS7**) and 165.10 µm (**JA3A**) gave the highest values of differential stresses yet obtained in Gemeric region: 245 ÷ 397 MPa (T.d., calculation with variation coefficient). The higher values in comparison with those in "typical localities" in Southern Gemericum we explain by frozing of the products of ductile deformation in frontal parts of the nappe without possibility of static recrystallization, reshaping of grains, growth of larger individuals and obscuring of former deformation twins from the state of dynamic recrystallization.

Carbonates and quartzites from the eastern contact zone between Gemericum and Veporicum

The calcite marbles behaviour during ductile shearing has been studied on sample locality Košice-Diana (**DI1**, **DI2**, **DI3**, AS_2 = *235/45*). Marbles showed dynamically recrystallized layers (medium to fine-grained) alternating with layers of flattened, elongated twinned grains

(Németh and Putiš, 1999). The textural patterns reflect both combined dislocation creep and mechanical e-twinning as the plastic deformation mechanisms. The representative grain size of marbles is 54.95 μm (**DI1**), 85.02 μm (**DI2**) and 95.19 μm (**DI3**). Differential stresses found from three marble samples by both methods are mutually comparable (cf. Tab. 1). As the most representative results are supposed those, reached by the Twin Density method calculated with variation coefficient **DI1** = 253.71 MPa, **DI2** = 230.16 MPa and **DI3** = 228.82 MPa.

The quartz paleopiezometry on quartzite samples **DI9**, **DI10** and **DI12** located in immediate vicinity of marble samples at Diana locality showed large diversity of results. Geologically the most meaningful results were obtained by calibration by Koch (1983): **DI9** = 151.3 MPa, **DI10** = 195.0 MPa and **DI12** = 169.8 MPa (Fig. 2). When comparing results from neighbouring calcite marbles and quartzites, the differential stresses in dynamically recrystallized quartzite horizon were lower. There is necessary to stress that the quartz paleopiezometry is based only on one parameter - the size of dynamically recrystallized grain. Therefore the results of calcite paleopiezometry calculating with more parameters (grain-size, number and orientation of deformation twins) can be supposed to be more credible. Despite weakness of quartz paleopiezometry, the tectonic reasons of lower differential stresses in quartzite bed than in marble bed are meaningfully explainable, as stated in the next chapter.

Discussion

Tectonization of Lower Paleozoic sequences

It is commonly known that polymineralic rocks are rheologically harder than monomineralic ones owing to their numerous phase boundaries and different internal free energies of minerals. Presented study, using known calibrations for monomineralic calcitic marbles and quartzites, states the differential stresses during tectogenesis in principal ductile shear zones in Gemeric region.

Because the absence of suitable monomineralic rocks directly in ductile shear zone between Gelnica and Rakovec Groups with kinematics of Variscan exhumation (Németh, 2002), our attempt to state differential stresses in Lower Paleozoic rock column was restricted to marble lenses from Holec Beds (Betliar Formation; Lower Paleozoic of Gelnica Group; cf. Fig. 2 in l.c.; Figs. 1 and 3).

More-or-less continual and homogenous horizon of black phyllites with organic matter (tectonization facilitated with fluid deliberation), located on lithologically and rheologically heterogeneous footwall (?variegated coarse-grained sediments, resp. ?Proterozoic basement), as well as hanging wall (variegated Lower Paleozoic sequences) satisfies conditions for preferred detachment plane. Strong rheological contrasts were effective after metamorphic compaction during Variscan orogeny. Moreover it is necessary to mention that this horizon, in difference to rocks of higher stratigraphic levels of Lower Paleozoic, very probable has not been deformed during south-vergent Variscan tectogenesis. Its primary "colmatage" position on significantly more rigid crystalline basement (with depressions infilled with coarser detritus) in comparison with "softer" plastic and relatively thin sedimentary and volcanic Paleozoic rocks in overlier, preserved this horizon in low differential stresses (compare results of paleopiezometry of sample GO1 and other Lower Paleozoic calcitic marbles in Table 1, Fig. 1). It is therefore very probable, that this rheologically distinct and tabular horizon of black phyllites of Betliar Fm., bearing interbeds of carbonates and lydites in its upper part, has been preserved against deformation till Cretaceous when it served as the main detachment horizon during Alpine overthrusting of Gemericum on Veporicum as well as internal imbrication in Gemericum (Fig. 3). The relative low differential stresses found in calcite lenses (**GO1**, **HO1** and **HO3;** compare Table 1, Fig. 1) are in accordance with the fact that the north-vergent overthrusting was accommodated by their host black phyllites. Based on results of regional meso- and microstructural analysis and overprinting relations (Németh, 2002) we correlate the deformation and recrystallization of carbonatic lenses of Holec Beds with Alpine AD_1 thrusting in Lower Cretaceous. The Alpine north-vergent reverse faulting – imbrication of Lower Paleozoic Gemeric sequences (marked with white arrows in Fig. 1 and AD_1b in Fig. 3) caused not only the superficial presence of thin strips of black phyllites of Betliar Fm. (with marbles and lydites of Holec Beds), but also several times repeated stratigraphy (Betliar Fm., Smolník Fm. and Hnilec Fm.) in generally E-W trending strips in central and southern parts of Gemericum.

Bôrka nappe - southern vs. northern occurrences

The north-vergent Bôrka nappe transport and emplacement were formerly characterized with LPO data of various kinds of tectonites (Németh, 2001). From this viewpoint the interesting result was brought by proof of NE-vergent sense of displacement in oriented marble sample from so-called Jaklovce Meliaticum (l.c.).

As paleopiezometry has showed us, the Bôrka nappe newly distinguished northern occurrences (**KS1A**, **JA3A**, **MS6**, **MS7**) demonstrate higher differential stresses than the Bôrka nappe marbles from the type localities in Southern Gemericum (**ŠU23B**, **ŠP20A**, **ZD1A**; Fig. 1). It can be explained by "frozing" of deformation in frontal parts of the nappe, while later exhumed parts had more time for recovery and ongoing static recrystallization. The complex evolution of Bôrka nappe marbles from Southern Gemericum is reflected in three generations of twins – the higher temperature usually bended twins of low number, being developed in large, totally recrystallized calcite grains (dimensions 300-400 μm), are overprinted by extremely numerous thin straight twins of razor type, and all these are penetrated by brittle low temperatures fractures.

Differential stresses during Alpine unroofing kinematics in the eastern part of contact zone between Veporicum and Gemericum

The superficial projection of the nappe emplacement of Gemericum on Veporicum in recent erosion cut is re-

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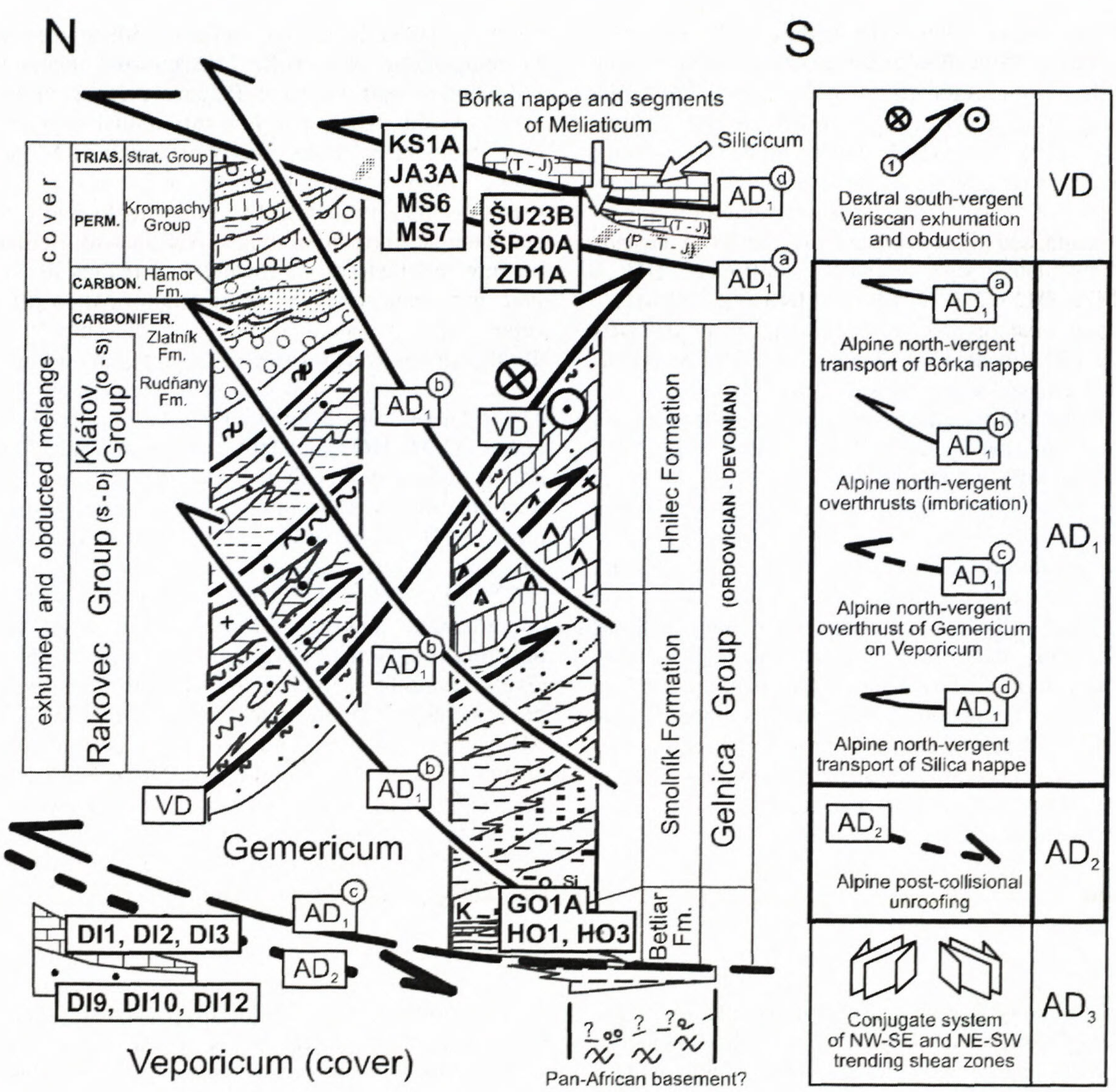

Fig. 3. Lithotectonic relations in Gemeric region (modified after Németh, 2001) and location of studied samples in lithotectonic horizons. Paleopiezometry documented differential stresses during dynamic recrystallization of selected samples during Alpine phases AD_1 and AD_2. For lithostratigraphic affiliation of studied samples, positioned in lithotectonic columns, see text and location of samples in explanation to Fig. 1.

presented with Lubeník-Margecany line. In the eastern – Margecany part of the zone, the mesostructural and microstructural evidences of the Gemeric nappe overthrust on Veporicum were given by numerous work (e.g. Jacko, 1978; Gazdačko, 1994; Jacko et al., 1996, 1997a,b).

The Alpine post-collisional unroofing, known formerly only in the western part of the contact zone (Upper Cretaceous tectonometamorphic ages; Maluski et al., 1993; Kováčik and Maluski, 1995; Dallmeyer et al., 1996), was revealed also in its eastern Margecany zone (Németh, 2001 and following works). The microtectonic research of deformation gradient in Margecany zone (l.c.) showed an important role of Triassic quartzites and carbonatic marbles of Veporic cover as the most softened horizons during Alpine ductile SW-vergent low angle normal faulting. The recent picture of apparently opposite kinematics of unroofing in the western and eastern part of the Lubeník-Margecany line was the product of shifting and rotation of rock blocks owing to displacement on conjugate system of shear zones of NW-SE and NE-SW directions with brittle-ductile to brittle shearing (AD_3; white half-arrows in Fig. 1; cf. Grecula et al., 1990; Gazdačko, 1994; Németh et al., 1997).

In attempt to document this process, the differential stresses from calcitic marbles (DI1, DI2 and DI3, Figs. 1 and 3, Tab. 1) as well as quartzites (DI9, DI10 and DI12) were determined and mathematically expressed. The presence of two monomineralic horizons contacting each other allowed us to test various calibrations of calcite and quartz paleopiezometry. From the large diversity of results for quartz paleopiezometry, the geologically most meaningful ones were obtained by calibration by Koch (1983) when inputting the average diameter of grains (Fig. 2). The differential stresses in dynamically recrystallized quartzite horizon were lower than in the case of marble horizons. This indicates, that (1) quartzite bed represented the softer medium than marble bed during the same tectonic process and smaller differential stresses were necessary for its kinematic activity, or (2) the marble bed was located closer to thrust plane (compare position of both beds in Fig. 3) and thus suffered higher differential stresses.

Conclusions

Research tested two methods of calcite paleopiezometry (Twinning Incidence and Twin Density, Rowe and Rutter, 1990) as well as quartzite paleopiezometry and obtained new data about the values of differential stresses accommodated by samples from principal ductile shear zones of Gemericum. Data are in agreement with recent interpretation of Alpine Lower Cretaceous overthrusting and imbrication during AD_1 phase, the Bôrka nappe transport through Gemericum and confirm and express the differential stresses during the post-collisional normal faulting AD_2 in the eastern contact zone between Gemericum and Veporicum.

When comparing both methods of calcite paleopiezometry – Twinning Incidence and Twin Density, the method of Twin Density with inputted variation coefficient 0.25 brought geologically best reliable and interpretable data. The Twin Density method takes into account not only number of grains with deformation twins, but the number of twins measured for the 1 mm distance perpendicularly to course of twins. This method is recommended for prior use in further tectonic research.

In the quartz paleopiezometry the calibration by Koch (1983), accounting the average diameter of grains, brought the results best converging to those of calcite paleopiezometry. When comparing results from neighbouring calcite marbles and quartzites, the differential stresses in dynamically recrystallized quartzite horizon were lower. This indicates, that quartzite bed represented either softer medium than marble bed during the same tectonic process, or marble bed was located closer to thrust plane.

New data contributed to geological and tectonic interpretation of geodynamic evolution of Inner Western Carpathians.

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