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Estimates of paleostress and paleotemperature conditions from naturally deformed calcite grain aggregates: Examples from Inner Western Carpathians, Slovakia

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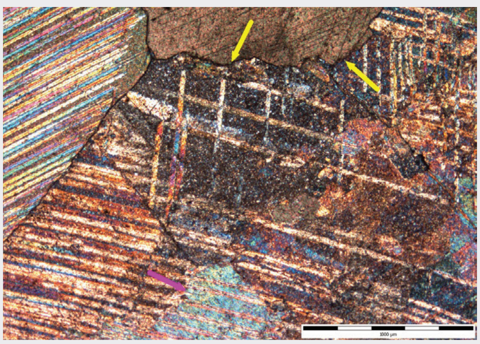
Abstract: Twin lamellae in calcite rocks or veins represent an important tool for determination of paleostress and paleotemperature conditions. To determine the values of paleostress in MPa, registered by the deformed monominerallic calcite rock or vein and expressed as differential stress ($\sigma_D = \sigma_1 - \sigma_3$), we used two paleopiezometric methods: Method of Twinning Incidence (I_t = twinned grains/total number of grains) and Twin Density (D = number of twins to 1 mm of the grain size perpendicular to twins). Measurements were done on marbles of the Bôrka Nappe (exhumed relics of the Meliata-Hallsttat Ocean) and calcite veins present in the Pieniny Klippen Belt (inferred suture zone after the Penninic Ocean). Presented paleopiezometric results document the differential stresses reached during the Meliata Unit Bôrka Nappe marble exhumation and thrusting over the Gemericum after the closure of the Meliata-Hallstatt Ocean. Whereas the deformed calcite veins from the Pieniny Klippen Belt, as a product of the last deformation event, provide the differential stresses related to the final deformation of the host rocks. Results of meaurements have proved the increase of the mean width of calcite twins (t – twin-width) by prograding temperature (T). The low twin width in marbles (t = 0.8–1 μm) was caused by deformation at low paleotemperature conditions (T = 170–200 °C). Compared to this, the calcite veins with twin width 9.4–15.9 μm indicate much higher paleotemperature conditions during their deformation (T > 250 °C). The grain-size of calcite crystals is decreasing with increasing differential stresses (σ_D), whereas the number of twins per 1 mm of perpendicular size of the grains (D) is increasing. The small grain-size in marbles (d = 23.7–58.2 μm) and high number of twins/1 mm (D = 73–646) is consequenced by high differential stresses (σ_D = 389.37–429.55 MPa). Opposing to this, the high grain-sizes in calcite veins (d = 450.5–516 μm) and low number of twins/1 mm of perpendicular size of the grains (D = 31–52) indicate lower differential stresses (σ_D = 203.48–240.44 MPa). The twin-length (l) is strongly dependent on the grain diameter (d) and represents a key parameter at calculations of the Volume of twins (V_{twins}). The low value of twin-length (l = 14.27–38.675 μm) in marbles is caused by the low grain-size (d = 23.7–58.2 μm), what is in contrast with results from calcite veins, where the high value of twin-length (l = 770.8–972.35 μm) was caused by the big grain-size (d = 450.5–516 μm). Due to low value of twin-length in marbles the volume of twins (V_{twins} = 37.7*10^3–251.9*10^3) is much lower in comparison to volume of twins in calcite veins (V_{twins} = 9.9*10^6–410.7*10^6), having the bigger twin-length.

Key words: paleopiezometry, differential stress, calcite grains, Twin Density, Twinning Incidence, Inner Western Carpathians

Graphical abstract



Highlights

- The principal parameters of the twinned grains in calcitic rocks are reviewed in relation to numerically revealed differential stresses
- Differential stress $\sigma_D = \sigma_1 - \sigma_3$ (MPa) represents a numeric value suitable for comparison of the strain in individual parts of the shear zone and such providing data for revealing the deformation softening and hardening, respectively.

1 Introduction

Nowadays numerous investigations deal with the rheological and mechanical behavior of rocks during their deformation. The strain of rocks is a result of a stress magnitudes, acting during deformation at a temperature. This paper focusses on mechanical twining on e-planes, which is a typical feature of naturally deformed calcitic rocks. It studies the relationship among individual parameters, including the computation of differential stress ($\sigma_D = \sigma_1 - \sigma_3$; MPa). The differential stress is a value usable for comparison of the strain mechanisms e.g. in individual parts of the shear zone (such as deformation hardening or softening), although it does not provide information about spatial orientation of individual stress axes.

The deformation process in the calcitic rock (coarse-grained limestone, marble or calcite-vein deformation) via the calcite crystals deformation is the stress and temperature-dependent, so it can roughly document also the metamorphic conditions during deformation if the differential stress numerically expressed. The works of earlier authors report the deformation characteristics for T < 300 ºC (Barber & Wenk, 1979), or even T < 400 ºC (Turner, 1953; Carter and Raleigh, 1969; Groshong, 1988).

Within the Western Carpathians, paleopiezometric research (Németh, 2005; Németh et al., 2012; Zákršmidová et al., 2016) was focussed on two principal tectonic zones:

The 1st group of paleopiezometric measurements related to the Middle-Late Jurassic closure of the Neotethyan (Meliata-Hallsttat) Ocean and its elements, forming Jurassic Mélange (cf. Krystyn & Lein in Haas et al., 1995), encompassing also the Western Carpathian Bôrka nappe (Mello et al., 1998; Aubrecht et al., 2010), which were subducted and subsequently thrust over the Gemeric Unit within the Inner Western Carpathians – IWC.

The 2nd group of paleopiezometric measurements was focussed on the Pieniny Klippen Belt (PKB), representing ca. 600-700 km long geosuture following the boundary of Inner/Outer Carpathians (e.g. Andrusov, 1965; Scheibner, 1968; Mahel', 1981; Birkenmajer, 1976a, 1986; Nemčok et al., 1998 in Jurewicz 2005). The name of the PKB is associated with the existence of two branches of Penninic Ocean, the South Penninic – Vahic Ocean and the North Penninic – Magura Ocean (Plašienka et al., 1997). The final ocean closure occurred no earlier than the Early Eocene (e.g. Oberhauser, 1991, in Ratschbacher et al., 2004).

Dependence of calcite twins on paleostresses

Paleostresses are expressed in exact numerical values as differential stresses (σ_D). They can be determined by two different methods (Rowe and Rutter, 1990): *Twinning Incidence* method *(I_t = twinned grains/grains total)* and *Twin Density* method *(D = twins/length)*, both in *MPa*. Another type of measurements takes into calculation the *Volume of fraction of twins (V_T = volume of twins/total volume)*, giving us the results in *μm^3*. This method is indirectly associated with previously mentioned piezometers.

The paleopiezometric measurements are based on the approaches by Jamison and Spang (1976), Lacombe (2007) and Laurent et al. (2000), who assumed that CRSS – Critical resolved shear stress (τ_c) is constant – about 10 MPa. According to Burkhard (1993) the deformation twins are developed at very low shear stress varying in between τ_c = 2–12 MPa, what is depending on temperature, as well as pressure conditions. The stress required to activate twinning is likely varying with the shear modulus, decreases with temperature (Rowe and Rutter, 1990). Twinning of calcite is a strain-hardening process, meaning that further twinning is resisted as beds tilt during subsequent deformation.

Dependence of calcite twins on paleotemperatures

The size of calcite grains increases with the increase of temperatues, leading to grain-boundary area reduction – GBAR mechanism, as a consequence of a static recrystallization – SR (Passchier and Trouw, 1996).

Not only the grain-size diameter, but also the width of calcite twins depends on paleotemperature. The morphology of calcite twins has been proposed as a geothermometer for low-grade metamorphic conditions (Burkhard, 1993; Ferrill, 1991; Ferrill et al., 2004).

The calcite twins deformed at temperature bellow T<170 ºC are thin, what is visible as thin black lines with their typical width less than 1 μm (Ferrill et al., 2004). Based on experimental deformation of calcite at higher temperature – T ≥ 300 ºC done by Ferrill et al. (2004), the thickness of individual twins may exceed 5 μm. Groshong (1974) suggested characteristic working definition of thin vs. thick calcite twins, pointed out their variable thickness strongly dependent on temperatures.

Burkhard (1993) and Ferrill et al. (2004) proposed following temperature dependent classification of twins: Type I – thin (<1 μm) and straight twins (T = 170–200 °C); Type II – thick (>1–5 μm) and slightly lensoidal twins (T = 150–300 °C), Type III – thick, curved and tapered twins, possibly re-twinned, accompanied by substantial dislocation glide (T > 200 °C), Type IV – thick and irregular twins, accompanied by a grain boundary migration (GBAR), indicating T > 250 °C.

In our research we have followed the previous studies, summarised in Németh (2005), Németh et al. (2012) and Zákršmidová et al. (2016), in which important parameters from paleopiezometric calculations have not yet been compared to each other. Paleostress and paleotemperature condidions represent the main factors influencing the shape, number and distribution of twins. We evaluate and compare the results from both suture zones – the Meliata Oceanic suture and the Penninic one.

2 Research method

2.1 Microscopic analytical techniques on calcite twins

Performed microscopic research of naturally deformed samples was based on calcite twin analysis. Studied samples were taken from the Meliatic fragments exposed on Gemeric Unit (Inner Western Carpathians), as well as from the Pieniny Klippen Belt – representing the boundary between the Inner and Outer Western Carpathians.

Careful preparation of thin sections excluded the fracturing or twinning grains during the sample preparation. Examined thin sections were then optically analysed by optical microscope Olympus VX 53, having attached the high-resolution digital camera LUMENERA. Using methods of calcite paleopiezometry (discribed in chapter 2.2) we measured 240 calcite grains in each sample to determine differential stresses.

Within each twin set we also measured: the average twin-width – t, number of twins per 1 mm of the perpendicular size of the grain – D, as well as grain-size – d. Twins, microfractures and pressure solution seams were present in large calcite grains, but the intense twinnig was regarded as the dominant deformation mechanism.

We quantified the density of calcite twins, as well as the percentage of grains with optically visible deformation twins using two calcite piezometers – *D (Twinn Density) and I_t (Twinning Incidence)* to obtain an estimate of the paleo-stresses governing deformation (*MPa*). We also determined the total volume of twins V_t *(Volume of twins/total volume)*. The average twin lamellae width was used for paleotemperature (*ºC*) estimations.

2.2 Differential stresses determination

Currently it is generally known that calcite twins represent an important tool to determine the differential stresses (Blenkinsop, 2000; de Bresser and Spiers, 1997; Masuda et al., 2011; Molli et al., 2011; Passchier and Trouw, 1996; Rybacki et al., 2011, 2013; Tullis, 1980; Turner, 1953; Wenk et al., 1983, 2006).

In our study, following previous studies by Rybacki et al. (2011, 2013), we focused on calcite paleopiezometry, being best calibrated for monomineralic calcite marbles with a pervasive ductile deformation (Rowe & Rutter 1990), as well as calcite veins which penetrated the whole volume of host rocks.

Calcite paleopiezometry is based on the size of dynamically recrystallized grains and the number and character of deformation twins. There are known two independent ways how to determine differential stresses in calcite rocks: *Twinning Incidence (It)* and *Twin Density (D)*.

Twinning incidence, I_t, is defined as the percentage of grains that demonstrates microscopically visible twins. During observation in thin section there were visible 1 or 2 twin sets.

The differential stress σ_D ($\sigma_1 - \sigma_3$; MPa) can be distinguished by the equation below, 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.

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

Twin density, D, is defined as the number of twins regarding the grain diameter, measured perpendicularly to the twins. To determine the twin density, the number of twins perpendicular to the twin boundaries within individual grains was counted and normalized to a unit length of 1 mm.

As shown by Friedman and Heard (1974), as well as Rybacki et al. (2013), twin density measurements using a flat stage match those measured with the universal stage to within 10 %. For maximum representativeness of provided data we performed twin density measurements at more than 3 different position to reach the maximum correctness. The standard error in this method is 43 MPa.

The relation of the differential stress on twin density D is as follows:

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

The primary data were obtained from thin sections, measuring the grain size in μm, as well as the number of deformation twins in corresponding grains. To guarantee the maximum representativeness of data, measurements were done systematically on profiles through the thin section, from grain to grain. Extreme dimensions (extremely small or large grains) were excluded from following calculations, using the variation coefficient 0.25, defined by Ranalli (1984). For numerical processing, a procedure consisting of several steps was developed (see in Németh, 2005).

Another type of piezometer is based on obtaining *the average volume of all twins – V_{twins} = volume of twins/total volume (μm³)*. The total fractional twin volume – V_T is the most important (Ferrill et al., 2004; Groshong, 1972; Chapter in Kocks et al., 1998), what equals to N_V – twins per unit volume of rock, as well as to V_{twins} – volume of all twins (Ferrill et al., 2004; Groshong et al., 1984 in Rybacki et al., 2013).

$$V_{T=}\ N_{V=}\ V_{twin}$$

For a randomly oriented oblate spheroids with their average length *l*, width *t,* and aspect ratio *q = t/l*, there were developed the below stated equations (Barnett et al., 2012; Dehoff and Rhines, 1961; Underwood, 1970 in Rybacki et al., 2013), using correlation between the product of twin density and twin volume (Groshong, 1972, 1974, and Groshong et al., 1984).

$$V_{twins} = \pi/6.\ D.q.l^3,$$

where D represents number of twins/1mm; t – twin-width and l – twin-length, q = t/l.

2.3 Twin width measuring for paleotemperature estimation

Supposing that the width and shape of the twins mirror the paleotemperature conditions, we performed measurements focusing on these parameters.

Because of the twin widths can not be easily measured using a flat-stage, we realized measurements including many twins with random deep angle according to the previous researches done by Underwood (1970). For a set of twins dipping at random angles to the traces, we measured the average of the true distances between adjacent boundaries by the equation below, stated by Rybacki et al. (2013), where *w (μm)* represents the average distances measured perpendicular to the traces of twins in thin section

$$w^* = 2/\pi \, . \, w$$

Our calculations were realized according to Ferrill et al. (2004), in which the "mean twin width" for a sample was evaluated by first measuring of the average twin width for each twin set (twin set average) and by second averaging the twin-set averages for the sample. The average of each twin set is calculated by summing the width of twinned material composed of both thick and thin twins. This sum was finally divided by the total number of twins in the set.

3 Results

The calcite twin data presented here are taken partly from previously published studies by Németh et al. (2012) and Zákršmidová et al. (2016). Recent study shows a noticable correlation of previously obtained results with new ones, which completed them.

The numeric estimations of differential stresses - paleostresses (σ_D, MPa) and paleotemperature (T, ºC) were based on measurements of following parameters: d – grain-size, l – twin-length, t – twin-thickness, D – no. of twins per 1 mm. Calculation of differential stress was performed by two different methods of paleopiezometry: It – Twinning Incidence, D – Twin Density, as well as the method of determination of Vt – Volume of fractures of twins. We pointed out the mutual relationships between all obtained values.

The obtained results are divided into *2 data sets*. *The 1st one* is represented by marbles and the *2nd* by calcite veins penetrating the host rocks.

1st set of data

The first set of samples (cf. Németh et al., 2012) contained six fine-grained limestones, representing five marbles of the Meliata melange nappe outlier with strong recrystallization (JAK-5, JAK-7, JAK-48, JAK-46, JAK-

Tab. 1

Twinning Incidence (It) and Twin Density (D) and calculated paleostress conditions in studied samples from the Kurtová skala hill – frontal part of the Bôrka nappe – "Jaklovce Meliaticum" (exhumed mélange of the Meliata-Hallsttat Ocean/Meliata Unit) thrust over the Gemeric Unit. The earlier laboratory paleopiezometry and computing, done by Zákršmidová (2012) in Németh et al. (2012), is completed by new results.

		Twinning Incidence (It)						Twin Density (D)			Twin Volume (Vt)		
	Representative grain-size - d	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.	Representative twin-length - l	Representative twin-thickness - t	Calculat. of the whole Vt (volume of twins/total volume)
		Calcul. with variation		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)	μm	μm	μm
Jak-5	23.7	269.40	12.22	268.72	272.07	269.40		173.05	330.95	347.49	38.675	0.8	136.2*10³
Jak-7	27.7	356.45	59.52	355.62	353.29	281.27		355.32	384.41	386.44	14.27	1.0	37.7*10³
Jak-46	40.06	411.63	100	407.79	405.79	408.52		481.61	407.93	406.73	19.65	1.0	98.7*10³
Jak-48	58.2	208.46	99.29	374.42	373.43	375.30		381.59	389.61	389.37	35.125	0.8	251.9*10³
Jak-54	42.2	407.15	100	403.40	403.73	404.25		428.88	429.55	429.55	20.3	0.8	139.5*10³

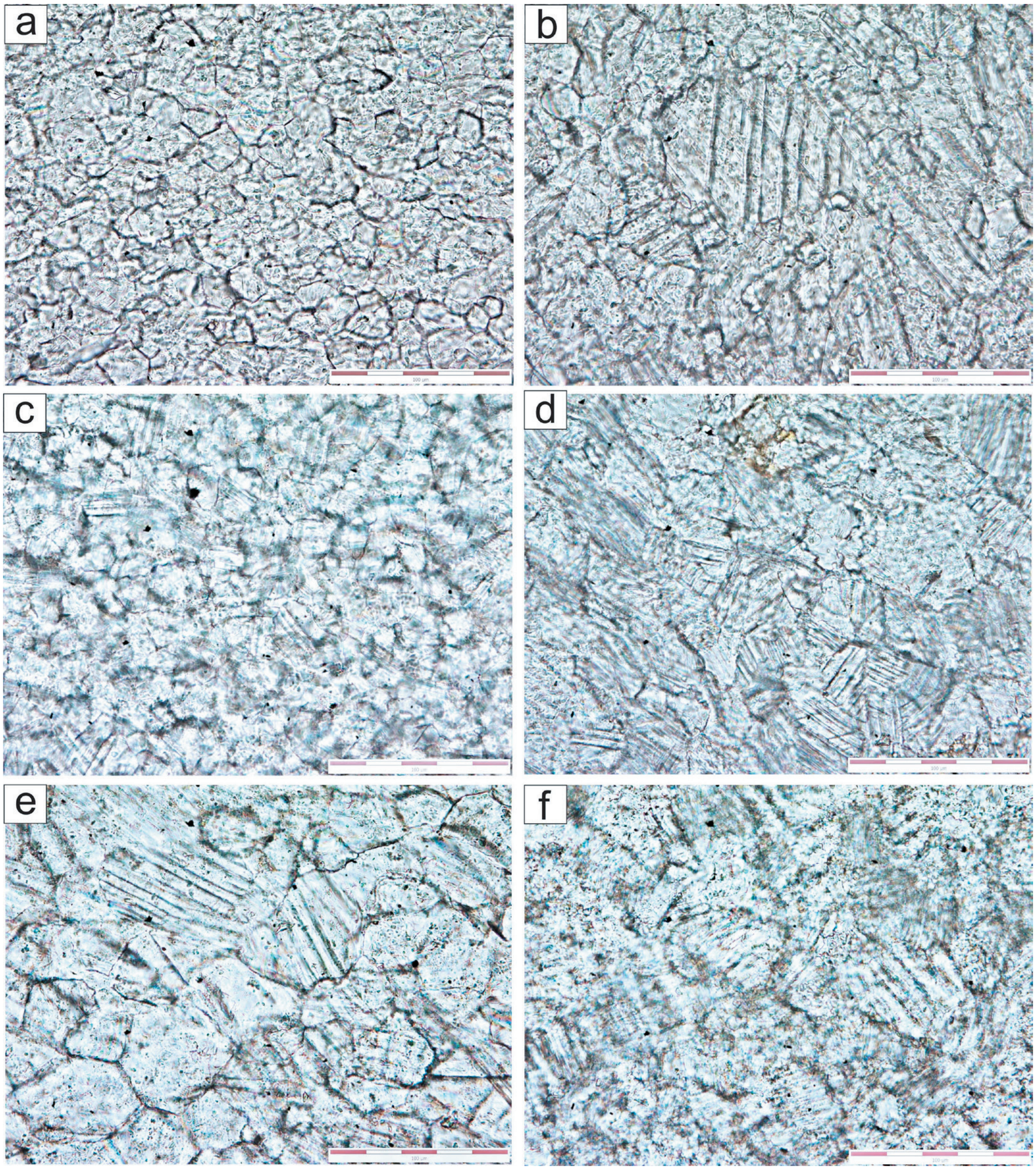


Fig. 1. Representative photomicrographs of undeformed (a) and deformed calcitic marbles (b-f) in plane-polarized light (PPL images), characterized by the single or multiple twin sets. The thin twins indicate the low-temperature (LT) conditions.

b-f – The high-strain deformation microstructures demonstrated by the bent twins, as well as high differential stresses (σ_D), Twinning Incidence (It) and Twin Density (D).

Other microscopic indicators, showing completely recrystallized calcite grains in marbles, except for the twinning, are as follows: boulging (BLG), subgrain rotation (SGR), grain boundary migration (GBM) and the grain boundary area reduction (GBAR).

a – JAK-4: Undeformed limestone, without microscopically visible twins, lying in autochthonous position beneath the deformed marbles (b-f) of the nappe outlier, transported by the kinematics of superficial nappe with remaining "frozen" high-strain state from the subduction zone (allochthonous body). Photomicrographs of studied samples are depicted with following parameters: d – average grain-size; l – twin-length; t – twin-thickness; It - Twinning Incidence – the percentage of grains with deformation twins; D – Twin Density – the average number of twins per 1 mm perpendicular to twin lamellae; σ_D – differential stress (MPa). The scale bar in each case (a-f) represents 100 µm. Plane polarized light.

b – JAK–5: d = 23 µm; l = 38.7 µm; t = 0.8 µm; It = 12.2; D = 330.95; σ = 347.49 MPa

c – JAK–7: d = 27.7 µm; l = 14.3 µm; t = 1.0 µm; It = 59.52; D = 384.41; σ = 386.44 MPa

d – JAK–46: d = 40.6 µm; l = 19.7 µm; t = 1.0 µm; It = 100; D = 407.93; σ = 406.73 MPa

e – JAK–48: d = 58.2 µm; l = 35.1 µm; t = 0.8 µm; It = 99.29; D = 389.71; σ = 389.37 MPa

f – JAK–54: d = 42.7 µm; l = 20.3 µm; t = 0.8 µm; It = 100; D = 428.88; σ = 429.55 MPa

54) and one limestone (JAK-4) representing the autochthonous footwall without recrystallization, being excluded from the further research. The study contributed to deciphering of the boundary between autochthonous cover limestones and allochthonous body of so-called *"Jaklovce Meliaticum"*, being exhumed from the Meliata-Hallstatt Ocean/Meliata Unit suture zone, located south of Gemericum, forming the Jurassic Mélange (e.g. Krystyn & Lein in Haas et al., 1995) and being transported over Gemericum (Dallmeyer et al., 1996; Putiš et al., 2011, 2014). The dynamic recrystallization was in studied thin-sections manifested also by bulging (BLG), subgrain rotation (SGR), grain boundary migration (GBM) or grain boundary area reduction (GBAR).

The stress field and recrystallization of the whole volume of calcite marbles caused the origin of deformation e-twins nearly in each calcite grain (Twinning Incidence – I_t up to 100 %; **Tab. 1, Fig. 1**). The twin densities (D) vary between **174** and **647 twins per 1 mm** at a very small size of grains, ranging from **24 to 58 (µm)**. The calcite paleopiezometry revealed the differential stresses (**σ_D**) within the range of **347.49-429.55 (MPa)**.

Other our measurements included the **average thickness of twins (t)**, ranging **from 0.8 to 1 µm** with the average spacing between them **from 0.5 to 0.8 µm**. We established the low temperature deformation conditions - less than 200 °C (sensu Burkhard, 1993) using obtained data, which suit to recrystallization in a subduction zone environment. The **twin-thickness (t)** represents an important parameter for calculations of the average volume of twins – **V_{twins}**. We have obtained results ranging from **$37.7*10^3$** to **$251.9*10^3$ µm^3**. We also measured a so-called "**key parameter**" – **twin-length (l)**, which was in the range of **14.27** and **38.68 µm**.

2nd set of data

The 2nd data set of thin-sections was compiled from representative samples from the Pieniny Klippen Belt (PKB), forming a boundary zone between the Inner Western Carpahians (IWC) and the Outer Western Carpathians (OWC). The sampling of a regional extent was focused on the interconnection zone between the older PKB shear system and younger Subtatric Ružbachy fault system (SRFS), which is localized in the eastern sector of this intricate belt system near the village of Chmeľnica.

We performed microscopic studies on specimens represented with twinned calcite veins (thick 5–15 cm) of regular shape, penetrating the whole volume of the host rocks – calcite grey marly limestones of Jurassic–Early Cretaceous age. In thin sections we distinguished more deformed older veins penetrated by less-deformed younger ones.

Within 240 measured calcite grains in each thin section (**Fig. 2**), we used the **grain-size diameter (d)** – varying from **450** to **516 µm**, as well as the **number of deformation twins (D)** with **31–52 twins per mm** of perpendicular diameter. These parameters provided the **differential stresses** (**σ_D**) ranging from **203.48** to **228.44 (MPa),** as can be seen in **Tab. 2.**

We also observed indicators connected with manifestations such as bulging – BLG, subgrain rotation – SGR, grain boundary migration – GBM, as well as grain boundary area reduction – GBAR mechanisms, tightly associated with the onset of static recrystalization – SR (polygonization of calcite grains). All these indicators are related to ductile deformation (Passchier & Trouw, 1996).

The average volume of twins **V_T**, ranging from **$9.9*10^6$ to $410*10^6$ µm^3** is the result of the **twin-length (l) 770.8-972.35 µm**, as well as **twin-thickness (t)** of **9.43–15.9 µm.** The results of twin-thickness, as well as the shape of twins

Tab. 2

Twinning Incidence (It), Twin Density (D) and Twin Volume (V_T), as well as differential stresses calculated for the calcite veins from the eastern sector of the PKB – Chmeľnica village.

		Twinning Incidence (It)					Twin Density (D)			Twin Volume (Vt)		
	Representative grain-size - d	Calcul. without variation coef. – Calcul. weight mean	It - for interval determined by variation coefficient	Calculation with variation coefficient – Calculat. with the whole It	Calculation with variation coefficient – Arith. mean of σ for size interval classes	Calculation with variation coefficient – Weight. mean of σ for size classes	D - no. of twins per 1 mm of perpend. diameter	Calculat. without variation coeffic.	Calculat. with variation coeffic.	Representative twin-length - l	Representative twin-thickness - t	Calculat. of the whole Vt (volume of twins/total volume)
	µm	σ (MPa)		σ (MPa)	σ (MPa)	σ (MPa)		σ (MPa)	σ (MPa)	µm	µm	µm
Jak-5	516	119.46	66	110.27	124.42	119.46	31	199.4	203.48	770.8	9.43	$9.9*10^3$
Jak-7	450.5	201.97	36	199.78	226.2	201.97	52	242.6	240.44	972.35	15.9	$410.7*10^3$

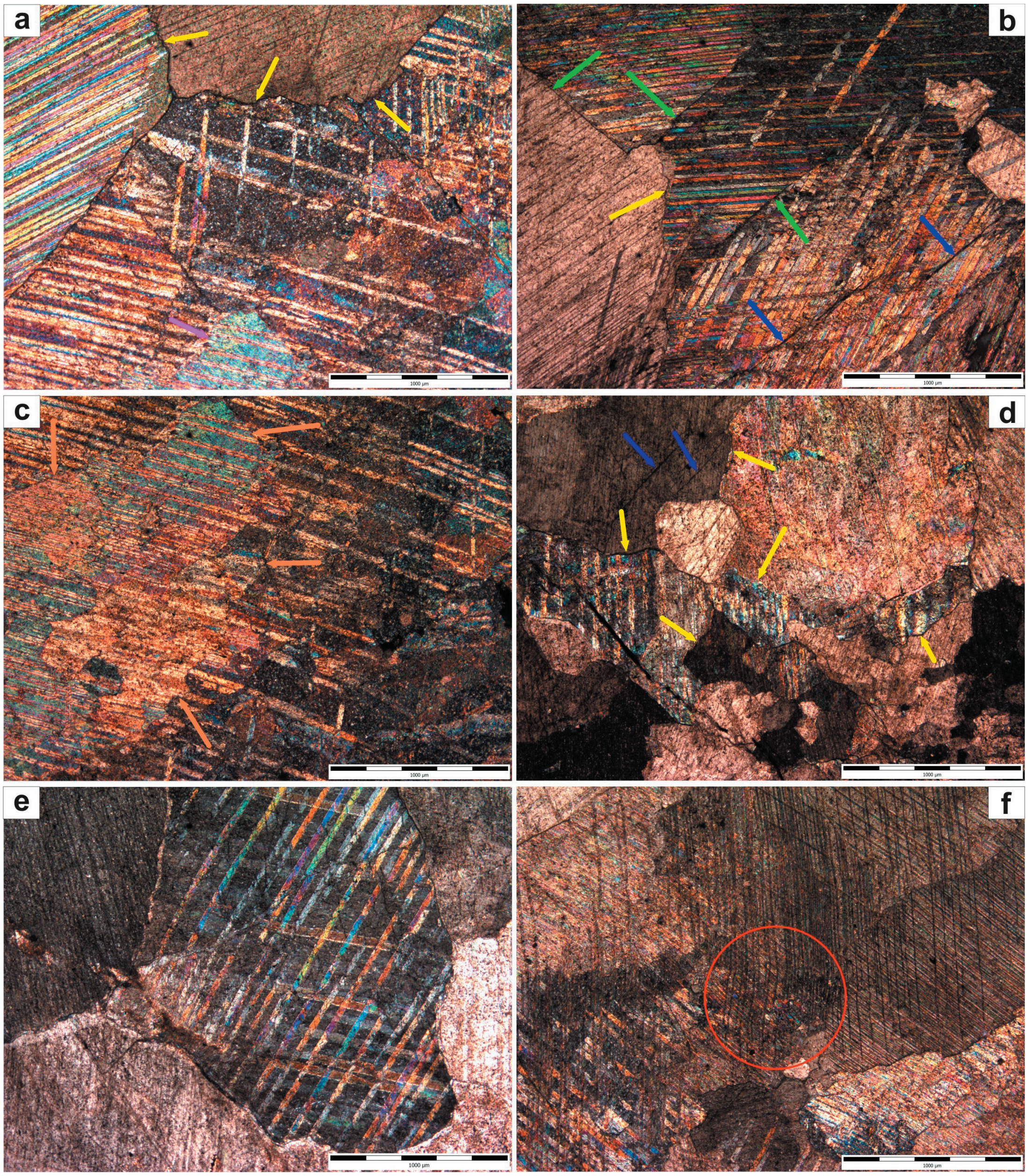


Fig. 2. Photomicrographs presenting the details of studied veins with twinned calcite. The veins are penetrating the whole volume of the Jurassic–Early Cretaceous marly limestone as a host rock. The Pieniny Klippen Belt, Western Carpathians.
Numerical expressions in the description below relate to following parameters: d – average grain-size, l – twin-length; t – twin-thickness; It - Twinning Incidence – the percentage of grains with deformation twins; D – Twin Density – the average number of twins per 1 mm perpendicular to twin lamellae; σ_D – differential stress (MPa). Photographs in crossed polarized light. Scale bar = 100 µm.
PKB3a: d = 516 µm; l = 770.8 µm; t = 9.4 µm; It = 66; D = 199.4; σ = 203.48 MPa (a, c, e)
PKB3b: d = 91 µm; l = 244.4 µm; t = 15.9 µm; It = 36; D = 242.6; σ = 240.44 MPa (b, d, f)
The deformed calcite veins in cross-polarized light (XPL images) are characterized by the single or multiple twin sets, developed mostly at different angles. The coarse-grained calcite in the vein manifest high twin density. The deformed calcite grains are slightly elongated or sub-isometric. The internal strain is achieved under the thin-thick-twin regime, which indicates the low-temperature conditions. Scale bar represents 1000 µm. **a –** deformation-induced textural re-equilibration in ductile / brittle-ductile transition regime; note grain-boundary bulging – BLG (yellow arrows; as well as in b-d); **b –** static recrystallization accompanied by grain boundary area reduction – GBAR manifested by polygonization (straight boundaries between calcite grains; green arrows). Microfractures are shown by blue arrows. **c –** Irregularly shaped calcite grains show the evidence of grain-boundary migration with forming of subgrains; **d –** bulging (yellow arrows); microfractures (blue arrows) and misoriented grain (pale-coloured grain close to the centre); **e –** large calcite grain with two sets of twins**; f –** bending of twin planes at high differential stresses (red circle). Bent thick twinning lamellae are produced during decompression (Pieri et al., 2001). Note twin lamellae cross-cuting host calcite crystals as in the case *e*.

point out on **low-temperature twinning conditions (below 200 °C** *sensu* Burkhard, 1993).

4 Interpretation and discussion

Twinning in calcite represents an important deformation mechanism of low-temperature conditions (150–300 °C) and it is leading mechanism during the high-pressure conditions (Groshong, 1972, 1988; Christian and Mahajan, 1995; Burckhard, 1993; Ferrill et al., 2004; Turner, 1964). Twinning begins at stress concentration on calcite crystals surfaces, grain boundaries, or other defects (Burkhard, 1993; Christian and Mahajan, 1995; Nicolas and Poirier, 1976).

We applied paleopiezometric measurements using two independent methods, such as Twinning Incidence (I_t) and Twin Density (D).

In the 1st data set (marbles), the revealed differential stresses were within the range of **347.49–429.55 MPa** (Németh et al., 2012).

These results together with previous researches (cf. Németh, 2005) have confirmed the allochthonous position of the Meliata (the Bôrka nappe) fragments in the North-Gemeric zone. Studied limestones, recrystallized due to subduction and subsequent exhumation represent a part of the Meliata-Hallsttat Jurassic Mélange (e.g. Krystyn & Lein in Haas et al., 1995). Presented results of our study in this topic are compatible with the research outcomes of Mello et al. (1998a, b); Mello et al. (1997); Ivan (2002); Ivan et al. (2009); Ivan & Méres (2009) or Putiš et al. (2011, 2012, 2014).

The 2nd data set presents the differential stresses within the range **203.48-240.44 MPa,** revealed from the calcite veins, penetrating the folded beds. The research was focussed on the interconnection of the older PKB tectonic system and younger Sub-Tatra Mts. Ružbachy fault system (SRFS), located in the eastern sector of PKB system. In the studied outcrop near the Chmelnica village, we identified three deformational phases. The studied calcite veins originated during second deformation phase from fluids migrating throughout the east-west trending joints and being ductilely overprinted during third deformation phase related to shearing along the Ružbachy fault system (Zákršmidová et al., 2016).

According to earlier structural researches, the entire deformatiom of the PKB units virtually occured under very low temperatures at diagenetic conditions, which is accompanied by brittle structures, followed by the diffusion mass transfer mechanisms, such as the 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 (e.g., Nemčok, M. & Nemčok, J.,1994; Jurewicz, 2005; Plašienka and Mikluš, 2010; Plašienka, 2012).

By means of high differential stresses accomodated by calcite grains (in limestones, or veins), leading to origin of ductilely deformed calcite crystals within examined samples, we have established empirical relationships among the most principal parameters, included into piezometric calculations, such as: **d (μm)** – *calcite grain-size,* **D** – *no. of twins per 1mm of the grain size, perpendicular to the grain*, **l (μm) –** *twin-length, **t*** **(μm***) – the average twin-thickness.*

4.1 Calcite grain-size – d (μm)

Twinning Incidence (I_t) vs. calcite grain-size (d)

Twinning Incidence (*It*) piezometer is based on a percentage of twinned grains regarding the whole number of grains. It provides results, which are independent on complexity of deformation history and orientation of the applied stresses (Rowe and Rutter, 1990). The differential stress revealed by the Twinning Incidence (It) piezometric method:

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

where I_t – *Twinning Incidence,* showing a percentage of grains with microscopicaly visible deformation twins and *d – grain-size*, the average diameter of grains.

The grain-size diameter decreases significantly with prograding deformation (mylonitization), and by this way also by increasing differential stress (σ_D). The low grain-sizes in marbles (23.7–58.2 μm) were produced by high differential stresses, which was numerically confirmed – σ_D = 347.49–429.55 MPa, as can be seen in **Fig. 3a.** On the contrary, the larger grain-sizes in calcite veins (450.5–516 μm) reflect the lower differential stresses σ_D = 203.48–240.44 MPa and higher temperature static recrystalization (cf. Passchier and Trouw, 1996), being depicted in **Fig. 3b.**

4.2 No. of twins per 1 mm of the perpendiculargrain size (D)

Twin Density (D) vs no. of twins/mm

Differential stresses determined by the *Twin Density* (*D*) method are calculated applying the equation – $\sigma_D = -52.0 + 171.1 \log D$ [MPa], where *D* – the number of twins/1mm.

In all samples the *no. of twins per 1 mm (D)* increased by prograding differential stresses *(σ_D, MPa)*, determined by *Twin Density (D)* paleopiezometry.

The high number of twins per mm (173.05–646.41) in marbles was caused due to high differential stresses – σ_D = 347.49–429.55 MPa.

Contrary to this in the calcite grains within veins is the number of twins per mm ranging between 31 and 52, which is much lower in comparison to marbles. It is due to lower differential stresses – σ_D = 203.48–240.44 MPa.

4.3 Twin-length – l (μm)

Volume of twins vs. twin-length

As was desribed before, the strain in rocks, accomodated by twins are expressed by several ways. One of them is also the total fractional twin volume, which is produced during deformation (Ferill et al., 2004; Groshong, 1972; Kocks et al., 1998).

Using the equation – $V_{twins} = \pi/6.\ D.q.l^3\ (\mu m^3)$, where *D* – no. of twins/1mm, *q* = *t/l*, *t* – twin-thickness, *l* – twin-length, we obtained new data about the volume fracture of twins (V_{twins} = volume of twins/total volume).

The result of V_{twins} (Volume of twins) is strongly depended on twin-lengths (l), which represent a so-called key parameter in calculation of V_{twins}. From the above stated equation it is supposed the linear relationship between V_{twins} *and* l_{twins}. On the basis of our measurements, it is evidenced that the low value of twin-length (14.27–38.68 μm) in marbles caused lower values of V_{twins} ranging from 37.7*10^3 to 251.9*10^3 (μm^3) in comparison to values yielded from calcite grains in veins, where twin-length in the range of 770.8 and 972.35 (μm) caused V_{twins} ranging from 99*10^3 to 410*10^3 (μm^3). The relations between measured values can be observable in the **Fig. 5 a, b.**

Twin-length vs. grain-size

The average twin-length (l) depends largerly on the grain-size, by which is the twin-length positively correlated. Lower value of twin-length (l) in the range of 14.27 and 38.68 (μm) is influenced by smaller grain-sizes parameters (23.7–58.2μm) in marbles, whereas in calcite veins are higher values of twin-length (9.43– 15.6 μm) caused

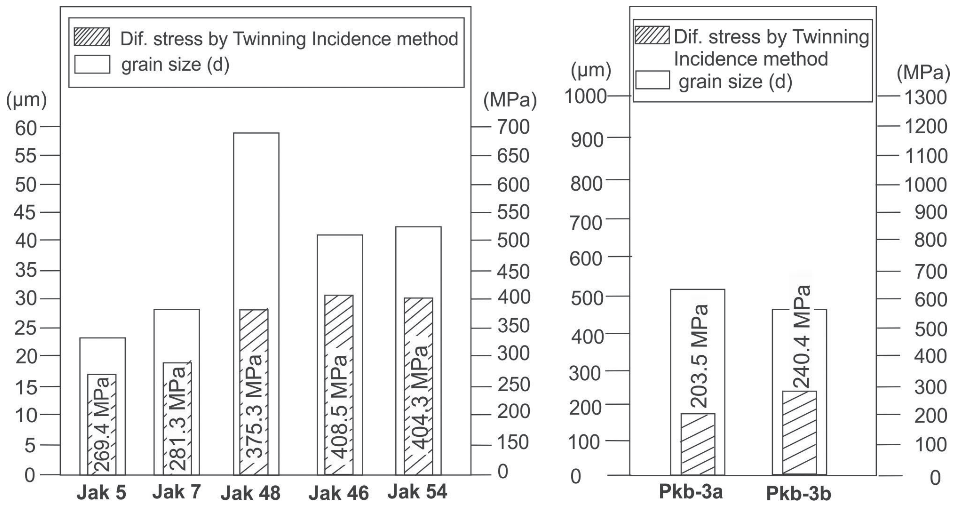


Fig. 3. a – The positive relationship between the differential stresses obtained by the Twinning Incidence method (σ_D, MPa) and grain-sizes – d (μm), except of the specimen – JAK-54 caused by SR – static recrystallization **b** – The negative relationship between Twinning Incidence – It (σ_D, MPa) and grain-sizes – d (μm) in comparison to marbles in **a**, caused due to higher temperature related static recrystallization.

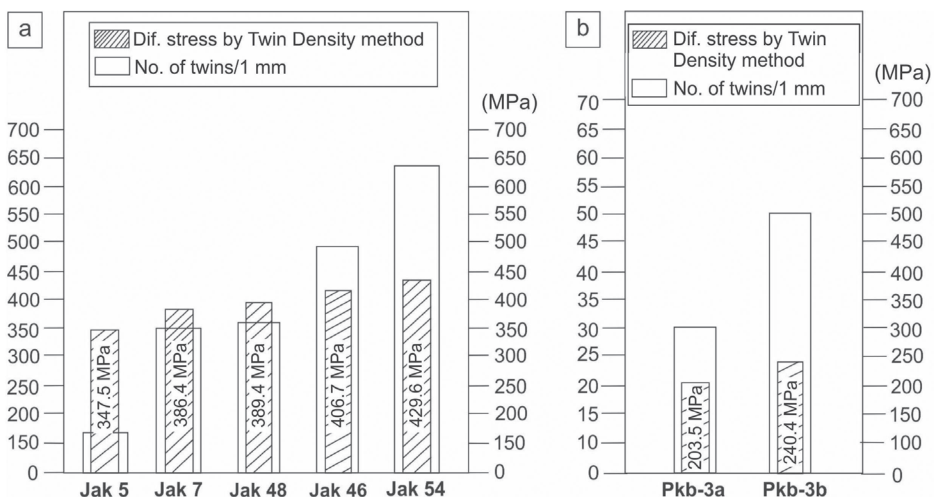


Fig. 4. a – The positive relationship between differential stress determined by the Twin Density method (MPa) and number of twins per 1 mm (D) in the 1st data set (marbles). **b** – The positive relationship between differential stress determined by the Twin Density method (D, MPa) and number of twins per 1 mm (D) in the 2nd data set (calcite veins).

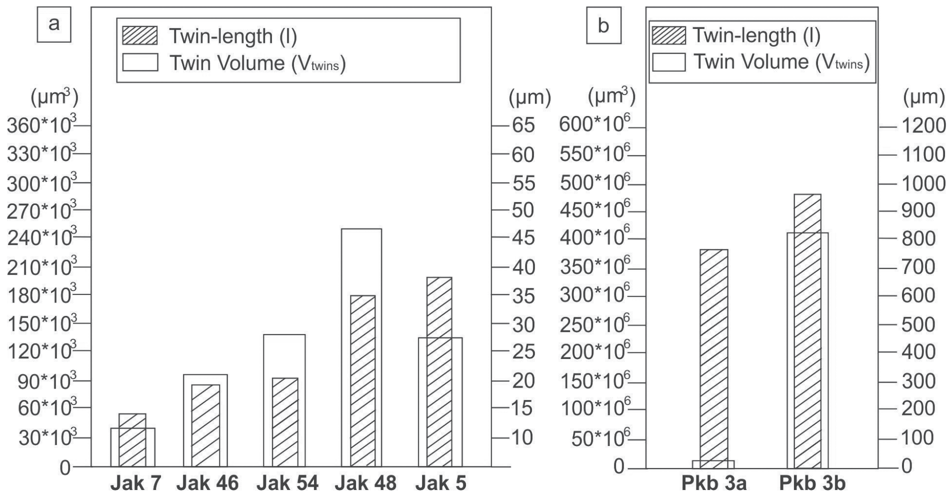


Fig. 5. The relationship between Volume of twins – V_{twins} and twin-length – l.

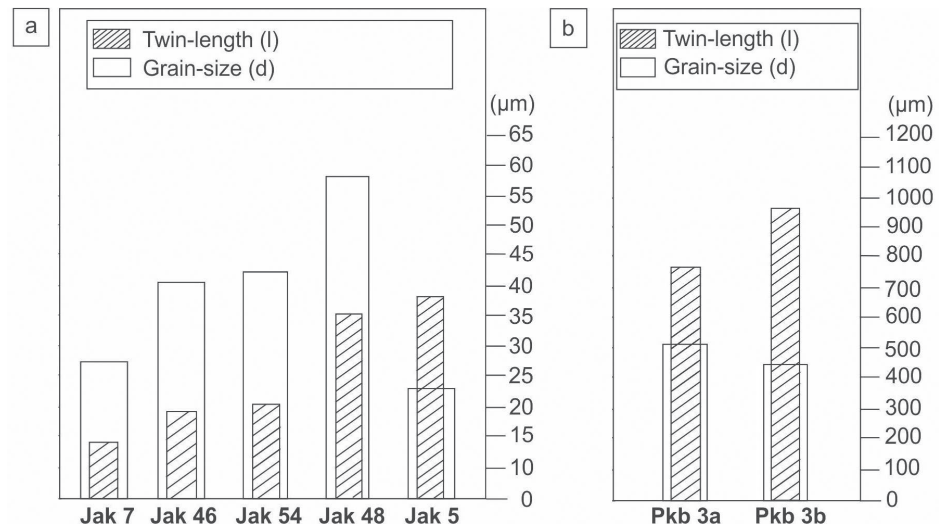


Fig. 6. The relationship between twin-length – l and grain-size – d.

due to larger grain-sizes (450.5–516 μm), as can be seen in **Fig. 6**.

4.4 The average twin-thickness (μm)

To determine the average volume of twins *(Vt)*, we studied characteristic indicators of twins for each grain-size interval *(d)*, among which belong the average thickness of twins *(t)*, as well as their average twin-length *(l)*. We followed previous observations in naturally strained carbonates (Burkhard, 1993; Ferrill et al., 2004 and Groshong et al., 1984). The all those researches showed that thick calcite twins predominate above 200ºC, while calcite twins formed below 200ºC are thinner.

The average thickness of twins in marbles was 1 μm with almost uniform spacing between them (ranging from 0.5 to 0.8 μm), what mirrors low temperature – *LT* conditions (T< 200ºC). Calcite grains within veins were thicker (up to 15.9 μm) with spacing between them, varying from 7 to 15 μm, as well as with manifistations of GBAR – grain boundary area reduction mechanism. It was consequenced due to higher temperatures (T > 250 °C).

The paleo-stress measurements realized within calcite crystal aggregates in marbles may approximate the peak metamorphic conditions. Those data from calcite veins, penetrating the whole volume of host rocks, may indicate a younger tectono-thermal reactivation from the final deformation stage.

5 Conclusion

Twins in calcite grains represent appropriate paleostress (differential stress–σ_D) and paleotemperature indicator for deformed calcitic rocks. Twinning piezometers according to Rowe & Rutter (1990) were used to determine the differential stress conditions during deformation of Meliata calcite marbles undergoing the subduction, exhumation and nappe displacement (the Bôrka nappe).

The multi-variant numerical processing followed the procedure by Németh (2005). The visualizations in this paper intend to present relationships between individual parameters included into paleopiezometric calculations: d – grain-size, D – number of twins per 1mm of the perpendicular dimension of the grain, l – twin-length and t – twin-thickness. As our research confirmed, the increasing number of deformation twins in marbles (D = 173–646) relates to increasing differential stresses (σ_D = 347.49–429.55 MPa). The lower number of deformation twins in calcite veins (D = 31–52) is resulting from lower values of differential stresses (σ_D = 203.48–240.44 MPa). The calcite grains in studied marbles had lower grain-size (d = 23.7–58.2 μm) in comparison to grains within studied calcite veins (d = 450.5–516). The grains-grain size (d) diameter is in positive relationship with twin-length (l), which ranged between 14.27–38.675 μm in marbles and 770.8–972.35 μm in calcite veins. Twin-length (l) and twin-thickness (t) represent key-parameters at calculations of V_{twins} – Volume of twins (Rowe & Rutter, 1990).

According to Burkhard (1993), taking into consideration the twin-thickness in marbles (t = 0.8–1 μm), we have estimated the low temperature conditions (T< 200 ºC), whereas in the case of deformed calcite veins with twin-thickness ranging between 9.43–15.9 μm we estimated the higher temperature conditions (T > 250 °C). In calcite veins there were revealed also related manifestations of GBAR – grain boundary area reduction mechanism = related to static recrystallization (Passchier and Trouw, 1996).

Visualizations in the paper show relationships between different parameters. The results are documenting the deformation paleo-conditions, which were "frozen" in studied samples, and such represent a contribution to reconstruction of geodynamic history.

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6 References

Aubrecht, R., Gawlick, H. J., Missoni, S., Suzuki, H., Plasienka, D., Kronome, K. & Kronome, B., 2010: Middle Jurassic matrix radiolarians from the Meliata ophiolite mélange at the type Meliatic sites Meliata and Jaklovce (Western Carpathians): palaeogeographic evidence. *Geol. Balc., 39, 33 – 34.*

Andrusov, D., 1965: Aperçu générale sur la géologie des Carpathes occidentales. *Bull. Soc. géol. France, 1 029 – 1 062.*

Barber, D. J. & Wenk, H. R., 1979: Deformation twinning in calcite, dolomite and other rhombohedral carbonates. *Phys. Chem. Miner., 5, 141 – 165.*

Barnett, M. R., Nave, M. D. & Ghaderi, A., 2012: Yield point elongation due to twinning in a magnesium alloy. *Acta Mater., 60, 1 433 – 1 443.*

Birkenmajer, K., 1976a: The Carpathian orogen and plate tectonics. *Publ. Inst. Geophys. Pol. Acad. Sci., A-2, 101, 43 – 53.*

Birkenmajer, K., 1986: Stages of structural evolution of the Pieniny Klippen Belt, Carpathians. *Stud. geol. pol., 88, 7 – 32.*

Birkenmajer, K., 1988: Exotic Andrusov ridge: its role in the plate-tectonic evolution of the West Carpathians foldbelt. *Stud. Geol. Pol.,* 91, *7 – 37.*

Birkenmajer. K., Kozur, H. & Mock, R., 1990: Exotic Triassic pelagic limestone pebbles from the Pieniny Klippen Belt of Poland: a further evidence for early Mesozoic rifting in West Carpathians. *Ann. Soc. Geol. Pol*., *60, 3 – 44.*

Blenkinsop, T., 2000: Deformation microstructures and mechanisms in minerals and rocks. *London, Kluwer Acad. Publ.*

Burkhard, M., 1993: Calcite twins, their geometry, appearance and significance as stress-strain markers and indicators of tectonic regime: a review. *J. struct. Geol., 15, 351 – 368.*

Carter, N. L. & Raleigh, C. B., 1969: Principal stress directions from plastic flow in crystalls. *Geol. Soc. Amer. Bull., 80, 1 231 – 1 264.*

Christian, J. W. & Mahajan, S., 1995: Deformation twinning. *Progress Mater. Sci., 39, 1 – 157.*

Dallmeyer, R. D., Neubauer, F., Handler, R., Fritz, H., Müller, W., Pana, D. & Putiš, M., 1996: Tectonothermal evolution of the internal Alps and Carpathians: Evidence from 40Ar/39Ar mineral and whole-rock data. *Eclogae geol. Helv., 89, 203 – 227.*

de Bresser, J. H. P. & Spiers, C.-J., 1997: Strength characteristics of the r, f, and c slip systems in calcite. *Tectonophysics, 272, 1 – 23.*

Dehoff, R. T. & Rhines, F. N., 1961: Determination of number of particles per unit volume from measurements made on random plane selections – the general cylinder and the ellipsoid. *Trans. Metall. Soc. AIME, 221, 975 – 982.*

Dumont, T., Wieczorek, J. & Boulin, J.-P., 1996: Inverted Mesozoic rift structures in the Polish Western Carpathians (High-Tatric units). Comparision with similar features in the Western Alps. *Eclogae geol. Helv., 89, 181 – 202.*

Ferrill, D. A., 1991: Calcite twin width and intensities as metamorphic indicators in natural low-temperature deformation of limestone. *J. struct. Geol., 13, 667 – 675.*

Ferrill, D. A., Morris, A. P., Evans M. A., Burkhard, M., Groshong, R. H. J. & Onasch, C. A., 2004: Calcite twin morphology: A low-temperature deformation geothermometer. *J. struct. Geol., 26, 8, 1 521 – 1 529.*

Friedman, M. & Heard, H. C., 1974: Principal stress ratios in Cretaceous limestones from Texas Gulf Coast. *Bull. Amer. Assoc. Petrol. Geol., 58, 71 – 78.*

Groshong, R. H., Jr., 1972: Strain calculated from twinning in calcite. *Geol. Soc. Amer. Bull., 82, 2 025 – 2 038.*

Groshong, R. H., Jr., 1974: Experimental test of least-squares strain gage calculation using twinned calcite. *Geol. Soc. Amer. Bull., 58, 1 855 – 1 864.*

Groshong, R. H., Jr., 1988: Low-temperature deformation mechanisms and their interpretation. *Geol. Soc. Amer. Bull., 100, 1 329 – 1 360.*

Groshong, R. H., Jr., Pfiffner, O. A. & Pringle, L. R., 1984a: Strain partitioning in the Helvetic thrust belt of eastern Switzerland from the leading edge to the internal zone. *J. struct. Geol., 6, 5 – 18.*

Groshong, R. H., Jr,, Teufel, L. W. & Gasteiger, C., 1984b: Precision and accuracy of the calcite strain-gage technique. *Geol. Soc. Amer. Bull., 95, 357 – 363.*

Haas, J., Kovác, S., Krystyn, L. & Lein, R., 1995: Significance of Late Permian-Triassic facies zones in terrane reconstructions in the Alpine-North Pannonian domain. *Tectonophysics, 242, 19 – 40.*

Ivan, P., 2002: Relics of the Meliata Ocean crust: Geodynamic implications of mineralogical, petrological and geochemical proxies. *Geol. Carpath., 53, 245 – 256.*

Ivan, P. & Méres, Š., 2009: Blueschist enclave in the Dobšiná quarry: The evidence of the relation of the ultrabasic body to the Hačava Fm. of the Bôrka nappe (Meliatic Unit, Slovakia). *Miner. Slov., 41, 4, 407 – 418.*

Ivan, P., Méres, Š. & Sýkora, M., 2009: Magnesioriebeckite in red cherts and basalts (Jaklovce Fm. of the Meliatic Unit, Western Carpathians): An indicator of initial stage of the high-pressure subduction metamorphism. *Miner. Slov., 41, 4, 419 – 432.*

Jamison, W. R. & Spang, J. H., 1976: Use of calcite twin lamellae to infer differential stress. *Geol. Soc. Amer. Bull., 87, 6, 868 – 872.*

Jurewicz, E., 2005: Geodynamic evolution of the Tatra Mts. and the Pieniny Klippen Belt (Wstern Carpathians). Problems and comments. *Acta geol. pol., 55, 295 – 338.*

Kocks, U. F., Tome, C. N. & Wenk, H. R., 1998: Texture and Anisotropy: Preferred Orientations in Polycrystals and Their Effect on Materials Properties. *Cambridge, Cambridge Univ. Press*.

Lacombe, O., 2007: Comparison of paleostress magnitudes from calcite twins with contemporary stress magnitudes and frictional sliding criteria in the continental crust: mechanical implications. *J. struct. Geol., 29, 86 – 99.*

Laurent, P., Kern, H. & Lacombe, O., 2000: Determination of deviatoric stress tensors based on inversion of calcite twin data from experimentally deformed monophase samples. Part II. Axial and triaxial stress experiments. *Tectonophysics, 327, 131 – 148.*

Masuda, T., Myake, S., Kimura, N. & Okamoto, A., 2011: Application of the microboudin method of paleodifferential stress analysis of deformed impure marbles from Syros, Greece: implications for grain-size and calcite-twin paleopiezometers. *J. struct. Geol., 33, 20 – 31.*

Maheľ, M., 1981: Penninic units in the Western Carpathians from the point of the view of global tectonics. *Miner. Slov., 13, 289 – 306.*

Mello, J., Elečko, M., Pristaš, J., Reichwalder, P., Snopko, L., Vass, D., Vozárová, A., Gaál, Ľ., Hanzel, V., Hók, J., Kováč, P., Slavkay, M. & Steiner, A., 1997: Vysvetlivky ku geologickej mape Slovenského krasu 1 : 50 000 (Explanations to geological map of the Slovak Karst 1 : 50 000). *Bratislava, GS SR, Vyd. D. Štúra, 1 – 255.*

Mello, J., Reichwalder, P. & Vozárová, A., 1998a: Bôrka nappe: High-pressure relic from the subduction-accretion prism of the Meliata Ocean (Inner Western Carpathians, Slovakia). *Slovak Geol. Mag., 4, 261 – 273.*

Molli, G., White, J. C., Kennedy, L. & Taini, V., 2011: Low-temperature deformation of limestone, Isola Palmaria, northern Apennine, Italy – the role of primary textures, precursory veins and intracrystalline deformation in localization. *J. struct. Geol., 33, 255 – 270.*

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. & Doneck, R.-A., 1998: Tertiary subduction and slab break-off model of the Carpathian-Pannonian region. *Tectonophysics, 239, 81 – 109.*

Németh, Z., 2005: Paleopiezometry: Tool for determination of differential stresses for principal ductile shear zones of Gemericum, Western Carpathians. *Slovak Geol. Mag., 11, 2 – 3, 185 – 193.*

Németh, Z., Radvanec, M., Kobulský, J., Gazdačko, Ľ., Putiš, M. & Zákršmidová, B., 2012: Allochthonous position of the Meliaticum in the North-Gemeric zone (Inner Western Carpathians) as demonstrated by paleopiezometric data. *Miner. Slov., 44, 1, 57 – 64.*

Neubauer, F., 1996: Kontinentkollision in den Ostalpen: *Geowissenschaften, 12, 136 – 140.*

Nicolas, J. & Poirier, J. P., 1976. Crystalline Plasticity and Solid State Flow in Metamorphic Rocks. *London, Wiley.*

Oberhauser, R., 1991: Westvergente versus nordvergente Tektonik – Ein Beitrag zur Geschichte und zum Stand geologischer Forschung, gesehen von der Ost-Westalpengrenze her. *Jb. Geol. Bundesanst., 134, 773 – 782.*

Passchier, C. W. & Trouw, R. A. J., 1996: *Microtectonics, 1 – 289.*

Pieri, M., Burlini, L., Kunze, K. Stretton, I. & Olgaard, D.-L. 2001: Rheological and microstructural evolution of Carrara marble with high shear strain: results from high temperature torsion experiments. *J. struct. Geol., 23, 9, 1 393 – 1 413.*

Plašienka, D., Grecula, P., Putiš, M., Kováč, M., & Hovorka, D., 1997: Evolution and structure of the Western Carpathians: An overview. In: Grecula, P., Hovorka, D. & Putiš, M. (Eds.): Geological evolution of the Western Carpathians. *Bratislava, Miner. Slov. – Monograph., 1 – 247.*

Plašienka, 2003: Dynamics of Mesozoic pre-orogenic rifting in the Western Carpathias. In: 5th Workshop of Alpine Geological Studies. *Mitt. Österr. mineral. Gesell., 94, 79 – 98.*

Plašienka, D., 2012: Early stages of structural evolution of the Carpathian Klippen Belt (Slovakian Pieniny sector). *Miner. Slov., 44, 1 – 16.*

Plašienka, D. & Mikuš, M., 2010: Geological structure of the Pieniny and Šariš sectors of the Klippen belt between the Litmanová and Drienica villages in Eastern Slovakia. *Miner. Slov., 42, 2, 155 – 178.*

Putiš, M., Danišík, M., Ružička, P. & Schmiedt, I., 2014: Constraining exhumation pathway in accretionary wedge by (U-Th)/He thermochronology – Case study on Meliatic nappes in the Western Carpathians. *J. Geodyn., 81, 80 – 90.*

Putiš, M., Koppa, M., Snárska, B., Koller, F. & Uher, P., 2012: The blueschist-associated perovskite-andradite-bearing serpentinized harzburgite from Dobšiná (the Meliata Unit), Slovakia. *J. Geosci., 57, 221 – 240.*

Putiš, M., Radvanec, M., Sergeev, S., Koller, F., Michálek, M., Snárska, B., Koppa, M., Šarinová, K. & Németh, Z., 2011: Metamorfovaná sukcesia silicitických bridlíc s bazaltom a diastrofickou brekciou v olistolite jurskej akrečnej prizmy meliatika pri Jaklovciach (Slovensko), datovaná na zirkóne (U-Pb SIMS SHRIMP) [Metamorphosed succession of cherty shales with basalt and diastrophic breccia in olistolith of the Meliatic Jurassic accretion wedge near Jaklovce (Slovakia), dated on zircon (U/Pb SIMS SHRIMP)]. *Miner. Slov., 43, 1 – 18* (in Slovak with English Summary).

Ranalli, G., 1984: Grain size distribution and flow stress in tectonics. *J. struct. Geol., 6, 443 – 447.*

Ratschbacher, L., Dingeldey, Ch., Miller, Ch., Hacker, B. R. & McWilliams, M. O., 2004: Formation, subduction, and exhumation of Penninic oceanic crust in the estern Alps: time constraints from $^{40}Ar/^{39}Ar$ geochronology. *Tectonophysics, 394, 155 – 170.*

Rowe, K. J. & Rutter, E. H., 1990: Paleostress estimation using calcite twinning: Experimental calibration and application to nature. *J. struct. Geol., 6, 443 – 447.*

Rybacki, E., Janssen, C., Wirth, R., Chen, K., Wenk, H. R., Stromeyer, D. & Dresen, G., 2011: Low-temperature deformation in calcite veins of SAFOD core samples (San Andreas Fault) – microstructural analysis and implications for fault rheology. *Tectonophysics, 509, 107 – 119.*

Rybacki, E., Evans, B., Janssen, C., Wirth, R. & Dresen, G., 2013: Influence of stress, temperature, and strain on calcite twins constrained by deformation experiments. *Tectonophysics, 601, 20 – 36.*

Scheibner, E., 1968: The Klippen Belt of Carpathians. In: Maheľ, M., Buday, T. et al. (Eds.): Regional geology of Czechoslovakia, II: The West Carpathians. *Praha, 304 – 371.*

Tullis, T. E., 1980: The use of mechanical twinning in minerals as a measure of shear stress magnitude. *J. geophys. Res., 85, 6 263 – 6 268.*

Turner, F. J., 1953: Nature and dynamic interpretation of deformation lamellae in calcite of three marbles. *Amer. J. Sci., 251, 276 – 298.*

Turner, F. J., 1964: Metamorphic Petrology: Mineralogy, field and tectonic aspects. *New York, McGraw Hill Book, 339 – 401.*

Underwood, E. E., 1970. Quantitative Stereology. *Addison-Wesley, Reading, MA.*

Wenk, H. R., Barber, D. J. & Reeder, R. J., 1983. Microstructures in carbonates. In: Carbonates: Mineralogy and Chemistry (ed. Reeder, R. J.). *Rev. Miner., Miner. Soc. Amer., 11, 301 – 367.*

Wenk, H. R., Rybacki, E., Dresen, G., Lonardelli, I., Barton, N., Franz, H. & Gonzalez, G., 2006: Dauphiné twinning and texture memory in polycrystalline quartz. Part 1: experimental deformation of novaculite. *Phys. Chem. Miner., 33, 667 – 676.*

Zákršmidová, B., Jacko, S. & Németh, Z., 2016: Paleopiezometry – the new investigation method applied to the Pienninic suture zone in comparison to Meliata-Hallstatt suture zone. *Acta Montan. Slov., 21, 43 – 52.*

Odhad paleonapäťových a paleoteplotných podmienok deformácie zŕn kalcitových agregátov: príklady z Vnútorných Západných Karpát

Deformačné lamely v kalcitových horninách či žilách sú užitočným nástrojom na určenie paleonapäťových a paleoteplotných podmienok zaznamenanej deformácie a rekryštalizácie kalcitových zŕn. Na určenie paleonapätia vyjadreného vo forme diferenciálneho napätia ($\sigma_D = \sigma_1 - \sigma_3$) sme použili dve nezávislé paleopiezometrické metódy: *Twinning Incidence* – metódu početnosti dvojčatenia (I_t = zdvojčatené zrná/celkový počet zŕn) a *Twin Density* – metódu hustoty dvojčatenia (D = počet deformačných lamiel/1 mm kolmého priemetu zŕn). Merania boli aplikované na mramoroch príkrovu Bôrky (exhumované relikty meliatsko-hallstattského oceánu) a na kalcitových žilách prestupujúcich celý objem horniny na viacerých odkryvoch v pieninskom bradlovom pásme (sutúrna zóna po penninskom oceáne). Berúc do úvahy tektonický vývoj meliatsko-hallstattskej sutúrnej zóny, paleopiezomtrické výsledky z deformovaných mramorov dokumentujú najvyššie zachované hodnoty diferenciálnych napätí, zatiaľ čo deformované kalcitové žily ako produkt posledných deformačných udalostí poskytujú diferenciálne napätia súvisiace s finálnou deformáciou. V študovaných vzorkách sme realizovali niekoľko sérií meraní, ktoré poukazujú na závislosť kalcitových deformačných lamiel od metamorfných podmienok. Na základe porovnávaní základných parametrov bolo dokázaných niekoľko skutočností.

Priemerná hrúbka deformačných lamiel (t – hrúbka lamiel) rastie s rastúcou teplotou (T). Malá hrúbka v mramoroch (t = 0,8 – 1 μm) je výsledkom nízkoteplotných podmienok kalcitových zŕn (T = 170 – 200 °C) bez ohľadu na napäťové podmienky. V porovnaní s tým kalcitové žily s hrúbkou t = 9,4 – 15,9 μm poukazujú na omnoho vyššie paleoteplotné podmienky (T > 250 °C). Veľkosť kalcitových deformovaných zŕn sa s narastajúcim diferenciálnym napätím (σ_D) zmenšuje, pričom počet deformačných

lamiel na 1 mm kolmého priemeru zrna (D) sa s narastajúcim diferenciálnym napätím zväčšuje. Malá veľkosť zŕn v mramoroch (d = 23,7 – 58,2 μm) a veľký počet deformačných lamiel/1 mm (D = 73 – 646) je dôsledkom deformácie pri veľkom diferenciálnom napätí (σ_D = 389,37 – 429,55 MPa). Naopak, väčšie rozmery kalcitových zŕn v kalcitových žilách (d = 450,5 – 516 μm) a malý počet deformačných lamiel/1 mm (D = 31 – 52) indikuje nižšie hodnoty diferenciálneho napätia (σ_D = 203,48 – 240,44 MPa). Dĺžka deformačných lamiel závisí od veľkosti priemeru kalcitových zŕn (d). Zároveň reprezentuje kľúčový parameter pri výpočtoch V_{twins} (objemu deformačných lamiel). Nízke hodnoty dĺžky deformačných lamiel (l = 14,27 – 38,675 μm) v mramoroch sú zapríčinené nízkymi hodnotami veľkosti zŕn (d = 23,7 – 58,2 μm), čo kontrastuje s kalcitovými žilami, v ktorých bola nameraná veľká dĺžka deformačných lamiel (l = 770,8 – 972,35 μm), narastajúca v závislosti od zväčšujúcich sa rozmerov deformovaných kalcitových zŕn (d = 450,5 – 16 μm). V prípade malej dĺžky lamiel bol vypočítaný objem deformačných lamiel (V_{twins} = 37,7*10^3 – 251,9*10^3) v kalcitových mramoroch omnoho nižší v porovnaní s objemom deformačných lamiel v kalcitových žilách (V_{twins} = 9,9*10^6 – 410,7*10^6), v ktorých je dĺžka deformačných lamiel omnoho väčšia. Vzájomné porovnania jednotlivých parametrov sú na obr. 3 – 6.

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