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Calcite deformation twins in Pohorje marbles

Deformacijski dvojčki v kalcitu pohorskega marmorja

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Abstract

Marbles in Pohorje occur in lenses and smaller bodies in the southern and southeastern part of the massif. Marbles are very pure, predominantly calcitic and rarely calcitic-dolomitic, containing a maximum of 5 % of non-carbonate mineral phases. The latter comprise pyroxenes (diopside), amphiboles (tremolite), olivines (forsterite) in places replaced by serpentine, quartz, feldspars (potassium feldspars and plagioclases), epidote, zoisite, vesuvianite, scapolite, muscovite, biotite partly replaced by chlorite, phlogopite, rare grains of titanite, rutile, zircone, apatite, and small grains of ferric oxides and sulfides. Calcite exhibits intensive deformational e-twinning whereas dolomite is undeformed and untwined. All four known types of mechanical twins in calcite were recognized: thin Type I twins, straight thick Type II twins, curved, lensoid and tapered thick Type III twins, and thick patchy Type IV twins. Type III twins are the dominant mechanical twins in the Pohorje marbles indicating the temperature of deformation somewhat above 200 °C. Since they lack signs of grain boundary recrystallization, we assume that the twinning was followed by a decrease temperature during exhumation. With increasing temperature the process of recrystallization along calcite grain becomes pronounced. Small individual untwined calcite crystals are progressively replacing bigger calcite grains. In few examples second generation of Type I deformational twins develop in recrystallized calcite grains, which also implies lowering of temperature due to exhumation.

Izvleček

Pohorski marmor se pojavlja v lečah in manjših telesih v južnem in jugovzhodnem delu pogorja. Marmorji so po sestavi zelo čisti, skoraj izključno kalcitni, izjemoma kalcitno-dolomitni in vključujejo največ do 5 % nekarbonatnih mineralnih faz. Te vključujejo piroksene (diopsid), amfibole (tremolit), olivine (forsterit) mestoma nadomeščen s serpentinom, kremen, glinence (kalijeve glinence in plagioklaze), epidot, zoisit, vezuvianit, skapolit, muskovit, biotit deloma nadomeščen s kloritom, flogopit, redka zrna titanita, rutila, cirkona in apatita ter majhna zrna železovih oksidov in sulfidov. Kalcitni kristali so močno deformirani z mehanskim dvojčenjem, dolomitni kristali pa so nedeformirani in brez dvojčkov. Našli smo vse štiri znane tipe mehanskih dvojčkov v kalcitu: tanke dvojčke tipa I, ravne in debele dvojčke tipa II, zakrivljene, lečaste in zašiljene dvojčke tipa III, ter debele krpaste dvojčke tipa IV. Prevlada dvojčkov tipa III v pohorskem marmorju nakazuje temperaturo deformacije nekoliko nad 200 °C. Ker ti dvojčki ne kažejo znakov rekristalizacije na robovih zrn, sklepamo, da je dvojčenju sledilo znižanje temperature zaradi ekshumacije kamnin. Z višanjem temperature postane bolj izrazit proces rekristalizacije vzdolž robov kalcitnih zrn. Velika kalcitna zrna so pri tem vedno bolj nadomeščena z majhnimi kristali brez mehanskih dvojčkov. V nekaj primerih so v rekristaliziranih kalcitnih zrnih nastali mehanski dvojčki tipa I druge generacije, kar tudi nakazuje zniževanje temperature zaradi ekshumacije.

Introduction

Deformation (or mechanical) twinning is an important mode of plastic deformation in carbonate minerals. Mechanical twinning is well known and characteristic in calcite, rare in dolomite, and almost absent in other carbonate minerals. Mechanical twins are often observed in coarse-grained carbonate rocks and/or veins that were deformed at temperatures below 400 °C (Turner, 1953; Carter & Raleigh, 1969; Groshong, 1988). Twin width and morphology are a function of temperature of deformation (e.g. Ferrill, 1991; Ferrill et al., 2004; and references therein). Twins in calcite deformed at low temperature are thin, less than 5 μm wide (Groshong, 1974; Groshong et al., 1984; Ferrill, 1991; Ferrill et al., 2004). With increasing temperature thick twins develop since higher temperature deformation allows twin widening to accommodate increasing strain (Heard, 1963; Ferrill, 1991; Ferrill et al., 2004). Thick twins are straight initially but bend with increasing temperature. Eventually, the recrystallization starts to occur at grain boundaries (Ferrill, 1991; Ferrill et al., 2004).

Twins in carbonate minerals were observed in different kinds of carbonate lithologies: marbles (e.g. Turner, 1953), unmetamorphosed and undeformed (e.g. Groshong, 1972; Groshong et al., 1984; Tourneret & Laurent, 1990; Ferrill, 1991; Lacombe & Laurent, 1992; and many references therein) or weakly deformed carbonate rocks (e.g. Tullis, 1980; Craddock & van der Pluijm, 1988). Twinning in carbonates is never a predominant deformation mechanism since even extensive twinning cannot accommodate large amount of strain (Barber & Wenk, 1979).

Here, we present a comprehensive study of deformational twin patterns in marbles from Pohorje. We use the frequency distribution of twin types to infer the temperature of deformation and the thermal history of the rocks, i.e. exhumation vs. burial.

Theoretical background

Deformation twins in carbonate minerals

Carbonates considered here are rhombohedral. The cleavage rhomb indexes in structural cell are {10$\bar{1}$4}, using four-digit Miller-Bravais hexagonal indices (e.g. Nicholas, 1966).

Calcite (CaCO3, space group R$\bar{3}$c) has dimensions of the hexagonal structural unit cell a=4.99 Å and c=17.06 Å. Twinning in calcite has been known for more than 150 years. Four different kinds of twins occur in naturally grown calcite (fig. 1), which include all possible twins that may form either during crystal growth or by deformation (Wenk et al., 1983; Bruno et al., 2010). These twin laws are expressed by the twin planes c = {00$\bar{1}$1}, r = {10$\bar{1}$4} , e = {01$\bar{1}$8}, and f = {01$\bar{1}$2} which coincide with the original composition planes. The main deformation twin law of calcite is on e-planes (Weiss & Turner, 1972; Barber & Wenk, 1979; Bueble & Schmahl, 1999), for which the shear displacement is in positive sense, in the direction < 0$\bar{2}$21 > (fig. 2a). The twinned (lower) layers of a crystal, which has positive e-axis upwards, are displaced in a sense opposed to the positive e-axis of the untwined layers. During deformation twinning the e-axis moves through an angle of 52.5 ° while the plane of the carbonate groups, which is perpendicular to the e-axis, must be rotated through the same angle (Barber & Wenk, 1979). Minor deformation twining in calcite may be observed also on r-planes and f-planes (Paterson & Turner, 1970), where the sense of r-twinning is positive (Weiss & Turner, 1972) and r-plane is the usual slip plane (Barber & Wenk, 1979).

Dolomite ($Ca_{0.5}Mg_{0.5}CO_3$, space group R$\bar{3}$) has lower symmetry than calcite due to the alternating layers of Ca and Mg atoms arranged parallel to the basal plane. Ca can exist in excess up to 0.25 apfu (atoms per formula unit) in non-stoichiometric dolomite, which are maximum substitutions the formula support (dos Santos et al., 2017). Additionally, Mg ions in dolomite may be partly substituted by Fe ions, producing isostructural mineral ankerite, or rarely Mn ions giving exotic mineral kutnahorite. For stoichiometric dolomite the lattice parameters of the hexagonal structural unit cell are a=4.81 Å and c=16.01 Å. Twin laws, also applying to deformation twinning, are dependent on symmetry characteristics (e.g. Dana

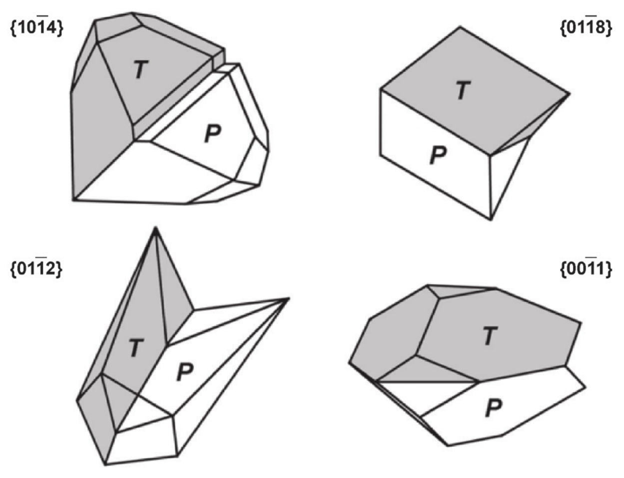

Fig. 1. The four twin laws of calcite (from Bruno et al., 2010). P–parent, T–twin.

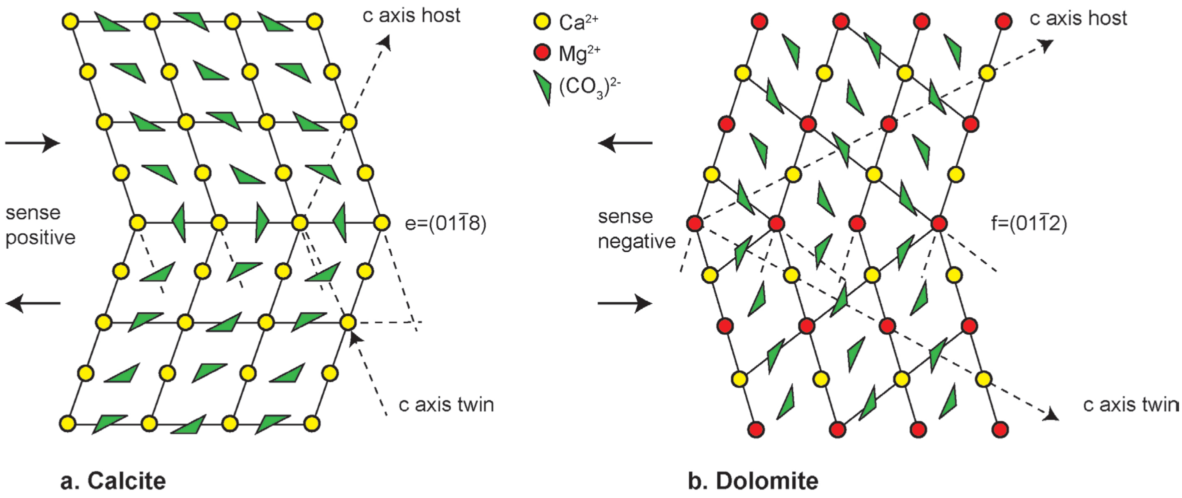

Fig. 2. Twining on (a) e-planes in calcite, sense positive, viewed along < 2$\bar{1}\bar{1}$0 > direction, and (b) f-planes in dolomite, sense negative, viewed along < 2$\bar{1}\bar{1}$0 > direction. The carbonate groups are denoted as triangles and lie in the {0001} planes parallel to the viewing direction. The triangles are drawn to indicate their alternate orientations in adjacent planes. See text for detailed explanation (redrawn from Barber & Wenk, 1979).

et al., 1951). As expected from its lower symmetry, dolomite possesses fewer twin forms than calcite, and only one type of deformation twinning is known (Barber & Wenk, 1979; Chang et al., 1998). It is expressed by f = {01$\bar{1}$2} twin plane which occurs within an f compositional plane. The shear displacement is in the < 0$\bar{1}$11 > direction (Barber & Wenk, 1979) and is negative in sense (Turner et al., 1954; fig. 2b). The f-plane is a usual slip plane for dolomite (Barber, 1977), and the resulting slip has positive sense (Barber & Wenk, 1979). Complete absence of e-twinning in dolomite which is the pervasive mechanism of mechanical twinning in calcite, is explained by dolomite composition, since the {01$\bar{1}$8} planes contain both Ca and Mg atoms, while the f planes do not. A shear on the e-planes would bring like species of cations into "closer-than-allowed" proximity (Bradley et al., 1953).

Among structural analogues of calcite, magnesite ($MgCO_3$), rhodochrosite ($MnCO_3$), and siderite ($FeCO_3$), only in rhodochrosite deformation twinning on e-planes is observed (Barber & Wenk, 1979). Due to structural similarities to dolomite, mechanical twinning on f-planes in ankerite and kutnahorite is reported (e.g. Barber & Wenk, 1979; and references therein).

Deformation twins in calcite as deformation temperature indicators

Calcite twin morphology, i.e. their width and intensity, may be used as low-temperature deformation geothermometer, especially in coarse-grained limestones or marbles that typically lack other indicators for deformation or maximum (peak) temperature (e.g. Burkhard, 1993; Ferrill et al., 2004; and references therein).

In calcitic rocks deformed at temperatures below 400 °C mechanical e-twinning is the main intracrystalline deformation mechanism (Turner, 1953; Carter & Raleigh, 1969; Groshong, 1988). With increasing temperature of deformation, four step changes in twin morphology may be observed (fig. 3). First are the thin Type I twins which form at very low temperatures (below 170 °C), followed by Type II straight thick twins forming at higher temperatures (above 200 °C). Type I twins are less than 5 μm thick and are visible only as thin black lines under the optical microscope. Type II twins are to > 10 μm thick with thickness measured as perpendicular distance between adjacent boundaries. The next step is characterized by bent and lensoid thick twins (Type III) that are frequently tapering towards the grain boundaries. Finally thick and patchy twins (Type IV) result from intensive recrystallization at grain boundaries (Schmid et al., 1980; Rowe & Rutter, 1990; Ferrill, 1991; Burkhard, 1993; Ferrill et al., 2004; Fig. 3). Dynamic recrystallization becomes an important deformation mechanism in calcite above 250 °C (Ferrill et al., 2004).

Mean calcite twin width correlates positively with temperature of deformation while mean twin density (twin planes/mm) correlates negatively (Ferrill et al., 2004). Twin densities in rocks deformed above 200 °C rarely exceed 400 twin planes/mm and cross plots of twin density with twin width can provide useful information about both strain and temperature of deformation (Ferrill et al., 2004).

The pattern of deformation microstructures may be used as a fingerprint for interpreting the thermal history. In case when twinning occurs at 200 °C during temperature increase (up to 300 °C),

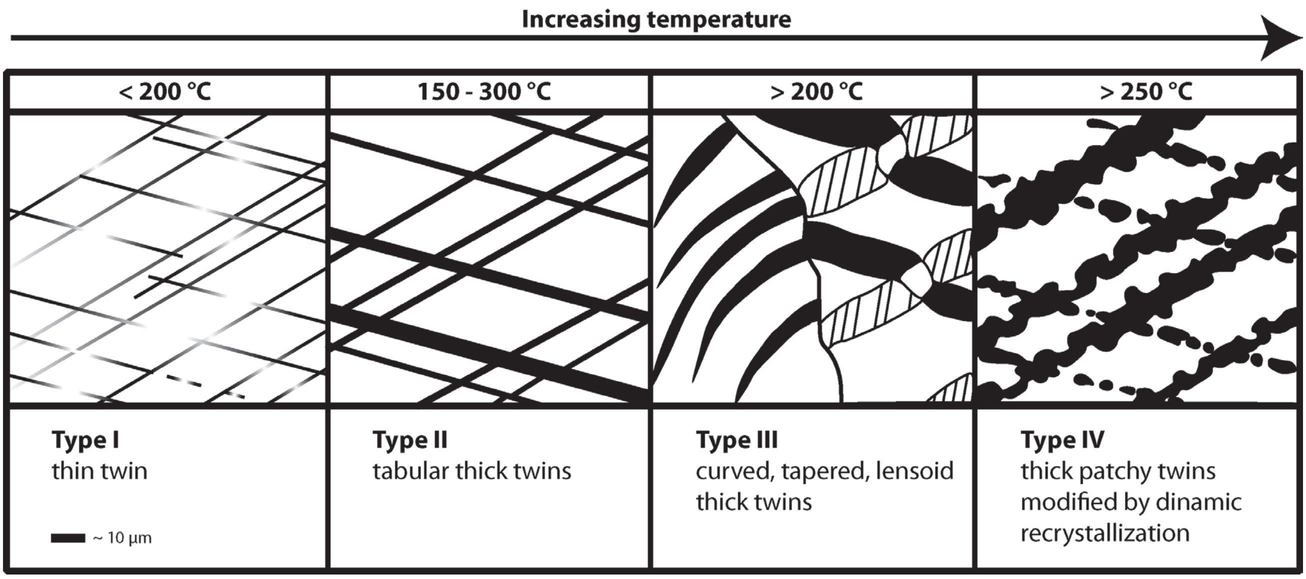

Fig. 3. Four different types of mechanical twins interpreted in terms of deformation temperature and mechanisms (after Ferrill, 1991; Burkhard, 1993; Ferrill et al., 2004).

calcite crystals will exhibit thick twins, grain boundary recrystallization, and recrystallization that has advanced inward from the grain boundaries. In contrast, when twinning occurring at 200 °C is followed by a temperature decrease, thick twins will lack signs of grain boundary recrystallization, and a greater abundance of thin twins will be present, some of those in the same set as the thick twins and others possibly even cutting through the thick twins (Ferrill et al., 2004).

Geological setting and sample location

Pohorje Massif forms the southeasternmost part of the Alpine chain and belongs to the Austroalpine units of the Eastern Alps. Its major structural unit, the Pohorje nappe (Janák et al., 2006) is composed of high-grade metamorphic rocs, mainly gneisses and micaschists which contain smaller bodies and lenses of amphibolites, eclogites, quartzites, and marbles (Mioč & Žnidarčič, 1977; Fodor et al., 2008; Kirst et al., 2010). A small body of ultramafic rocks occurs at the southeastern margin of the massif (Slovenska Bistrica Ultramafic Complex – SBUC; Janák et al., 2006) comprising strongly serpentinized harzburgites and several smaller bodies of better preserved garnet peridotites (Hinterlechner-Ravnik, 1987; Janák et al., 2006; De Hoog et al., 2009). Pohorje massif was subjected to metamorphism in the Late Cretaceous (ca. 95–92 Ma; Thöni, 2002; Miller et al., 2005; Janák et al., 2009) when these units reached conditions within stability field of diamond (Janák et al., 2004, 2006, 2015; Vrabec et al., 2012). The major exhumation of the Pohorje nappe, from ultrahigh pressure depth to mid crustal levels most probably occurred already during the Upper Cretaceous, similarly to the Koralpe area, the north-westward extension of the Pohorje nappe, where Upper Cretaceous (75-70 Ma) cooling ages were determined (Schuster et al., 2004). The final stage of exhumation to the surface was achieved in the Early to Mid Miocene by east- to north-east-directed low-angle extensional shearing, associated with the main opening phase of the Pannonian basin and leading to the core-complex structure of the Pohorje Mountains (Fodor et al., 2008). The Miocene shearing event reactivated and overprinted the nappe boundaries in the Pohorje area (Janák et al., 2006; Fodor et al., 2008).

The central part of Pohorje is intruded by the igneous body of granodioritic to tonalitic composition (Zupančič, 1994). The main intrusion was followed by the formation of aplite and pegmatite veins and in the western part of Pohorje also by shallow dacite bodies and dykes. In the southern part of the pluton a small body of dioritic composition is preserved (Faninger, 1965; Jarc et al., 2017). Granodiorites and pegmatites intruded in the host rocks in Miocene time (Altherr et al., 1995; Fodor et al., 2008; Trajanova et al., 2008; Uher et al., 2014).

Marbles occur in forms of lenses and smaller bodies mainly in eastern and southern part of Pohorje (fig. 4), where also some small isolated marble quarries are located (fig. 5). Their country rocks are mainly gneisses and micaschists. In some places, marbles are intercalated with lenses and boudins of darker amphibolitic material and

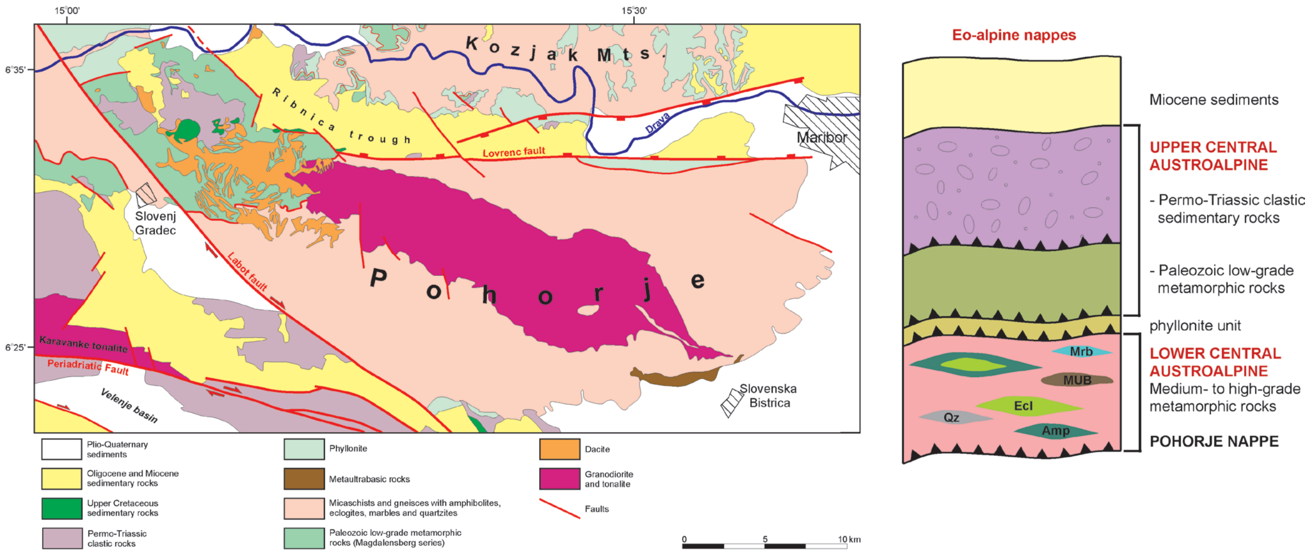

Fig. 4. Simplified tectonic map of Pohorje and succession of tectonic nappes in Pohorje in cross section (modified after Mioč & Žnidarčič, 1977).

sheets of silicate leucocratic material. Marble outcrops in the close vicinity of the main magmatic intrusion are commonly cut by aplite veins in different orientations. Aplite veins in horizontal orientations are sometimes extensionally torn into boudins while those in vertical direction show typical ptygmatic folding due to simultaneous vertical shortening (fig. 5). The composition and structure of Pohorje marbles was previously described by Jarc & Zupančič (2009) and Jarc et al. (2010).

Samples were taken from 25 localities outcropping in the eastern and southern part of Pohorje as shown on Fig. 6. Where possible, the samples were taken in the oriented position.

Methods

To perform reliable measurements of deformation twin lamellas in calcite grains, oriented thin sections are obligatory. It is difficult to observe twin lamellae that are subparallel to a thin section. The stochastic modelling of this effect showed that 20-25 % of twin lamellae can be overlooked due to this effect, depending on the skills of the operator (Yamaji, 2015). In order to diminish this effect as much as possible, we prepared polished thin sections from several sample in three perpendicular orientations.

From 25 localities (fig. 6) 104 polished thin sections were prepared and analyzed under the optical microscope in plain polarized light. In all thin sections, the presence of different types

Fig. 5. (a) Part of the Roman Quarry north from Slovenska Bistrica was used as the source of marble already in Roman times. Relict bedding and numerous aplite veins in different orientations may be observed. The vertically oriented aplitic vein on the left side of the picture displays prominent ptygmatic folds. (b) Boudins of aplite in marble.

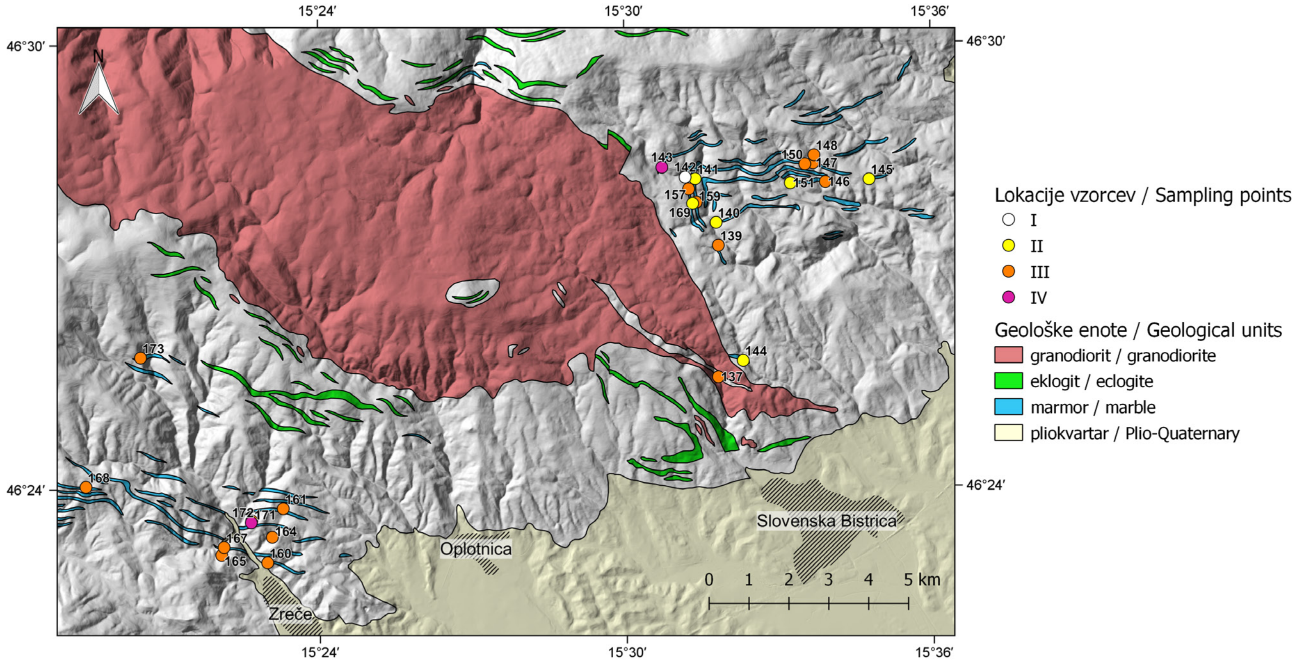

Fig. 6. Simplified geological map of southeastern Pohorje, based on Mioč & Žnidarčič (1977) and Žnidarčič & Mioč (1989), showing the locations of marble sampling locations. The main granodioritic intrusion as well as larger marble lenses and eclogite/amphibolite lenses are outlined. Different colors of the sampling localities correspond to the dominating type of twins found at respective locality: Type I, Type II, Type III, and Type IV.

of twins was quantitatively estimated. The proportion of non-carbonate mineral phases was neglected because in most cases they are present only in small amounts. The degree of recrystallization and the percentage of non-twinned calcite grains were estimated.

Results and discussion

Petrography and mineralogy

In macroscopic observation, marbles from Pohorje are white, only in rare occasions they show areas of pinkish, greyish or brownish coloring. In some samples laminas, layers or lenses of darker colored material of amphibolitc composition are present. All marble samples are crystalline medium- to coarse-grained; in some cases, granoblastic texture is pronounced.

In microscopic view, Pohorje marbles are mostly calcitic marbles. Very rarely calcitic-dolomitic species were detected; and even then, the dolomite was subordinate. All samples are very pure marbles since they contain less than 5 % of non-carbonate mineral phases. These non-carbonate minerals sometimes occur as individual grains evenly/randomly distributed in the samples but more often, they are found in form of lenses or laminas heterogeneously penetrating the samples. Among main non-carbonate minerals we detected pyroxenes (diopside), amphiboles (tremolite), olivines (forsterite), quartz, feldspars (potassium feldspars and plagioclases), epidote, zoisite, vesuvianite, scapolite, muscovite, biotite, phlogopite, rare grains of titanite, rutile, zircone, apatite, and small ferric oxides and sulfides. Chlorite and serpentine minerals are found as secondary phases, first replacing biotite and second replacing olivines.

The discovery of scapolite, vesuvianite and olivines that the maximum temperature conditions of metamorphism of 500 °C reported by Jarc et al. (2010) may be underestimated. Moreover, according to work of Janák et al. (2015), the Pohorje metamorphic terrane represented a coherent unit during peak ultrahigh-pressure metamorphism in the Late Cretaceous (c.95– 92 Ma) and during the subsequent exhumation. Therefore the marble lenses must have been exposed to the same peak pressure and temperature conditions of ≥3.5 GPa and 800–850 °C as the rest of the unit (Janák et al., 2015), but the marbles apparently did not preserve indicators of this peak pressure and temperature conditions.

The non-carbonate minerals often occur in lenses and seams heterogeneously penetrating marble samples. This random distribution may be interpreted in two ways. First, it can represent the pathways of fluids percolating through the carbonate material during metamorphism, or it may represent the remnants of non-carbonate precursor lithologies in parent carbonate rocks.

Deformation twins

In all investigated marble samples from Pohorje the mechanical twins were detected only in calcite grains. In calcitic-dolomitic marbles, all dolomite grains were clear and undeformed. Twinning in calcite occurs predominantly at low temperatures, and is characterized by the generation of large numbers of glide dislocations, while in dolomite it is more common at high temperatures (Barber & Wenk, 1979). Therefore, one of the reasons why twinning in naturally deformed dolomite rocks is less common and less abundant than e-twinning in calcite marbles is because dolomite does not twin at low temperatures. Moreover, at the range of temperatures we inferred for deformation of the Pohorje marbles, dolomite grains in calcite-dolomite composites remain completely rigid whereas calcite is considerably weaker and will display various crystaloplastic deformation mechanisms (Davis et al., 2008; Kushnir et al., 2015).

In marble samples from Pohorje all four types of mechanical e-twins in calcite are present. Thin twins of Type I (Fig. 7a) are prevailing type of e-twining only in samples from Kresnik area (Site No. 142 in and in Fig. 6). Twins are not exceeding 5 μm in width and are seen as tiny lines crosscutting bigger calcite grains. In subordinate amount, Type I twins are present also in samples from six other localities (Table 1). Tabular thick

Table 1.Twin frequency distribution in Pohorje marbles. Percentage of each type of twins was calculated using all available samples per locality. The untwined area includes also the recrystallized grains when they do not show secondary deformational twinning. The dominant twin type at each locality is marked with shaded cell.

Location	Samples	Type I	Type II	Type III	Type IV	Untwined	Recrystallization
Rimski kamnolom	137-1a, b, c; 137-4, 137-9	10 %	20 %	30 %	-	40 %	M
Motaln	139-1a, b, c; 139-2	10 %	30 %	50 %	-	10 %	M
Pregl	140-2, 140-4	20 %	70 %		-	10 %	W
Velika Polskava	141-1a, b, c; 141-3	-	60 %	20 %	-	20%	M
Kresnik	142-1	60 %	40 %		-	0 %	N
Surč	143-1, 143-2, 143-3, 143-5	-	-	10 %	20 %	70 %	EXT
Zgornja Nova Vas	144-1, 144-2, 144-3a, b, c; 144-4, 144-4, 144-5, 144-6, 144-6a, 144-7, 144-8, 144-8a	15 %	40 %	15 %	-	30 %	W-M
Planica	145-1a, b, c, d, e; 145-2a, b, c; 145-3	-	45 %	25 %	-	30 %	W-M
Sveti Križ	146-1a, b, c; 146-2	-	25 %	45 %	-	30 %	W
Nacek	147-1, 147-2	-	10 %	30 %	20 %	40 %	S
Vešnarjeva jama	148-1a, b, c; 148-2	-	20 %	50 %	10 %	20 %	VS
Vešner	150-1	-	35 %	50 %	-	15 %	M
Bavhnik	151-1	10 %	40 %	20 %	-	30 %	M
Kresnikova lipa	157-1/1, 157-1/2, 157-2, 157-3a, b, c; 157-4, 157-5	-	25 %	55 %	-	20 %	W-M
Bojtina	159-1/1, 159-1/2, 159-1/3, 159-2/1, 159-2/2, 159-3, 159-4, 159-6,159-7, 159-8, 159-9a, b, c; 159-10	-	20 %	40 %	20 %	20 %	VW-W
Orlovo gnezdo	160-1, 160-2, 160-3	-	10 %	50 %	30 %	10 %	W
Črešnova 1	161-1, 161-2, 161-3	-	-	40 %	30 %	30 %	M
Klančnik	164-1, 164-2	-	-	50 %	-	50 %	S-VS
Jozl 1	165-1, 165-1a, b; 165-2	-	-	50 %	10 %	40 %	VS
Jozl 2	167-1	-	-	50 %	20 %	30 %	S
Gorjak	168-1, 168-2, 168-3	-	-	70 %	10 %	20 %	S
Trmot	169-1, 169-2	10 %	40 %	30 %	-	20 %	N
Gorenje 2	171-1, 171-2	-	10 %	40 %	20 %	30 %	M-S
Gorenje 3	172-1, 172-2, 172-3, 172-4	-	-	20 %	40 %	40 %	M-S
Ločnikar	173-1, 173-2/1, 173-2/2	-	-	40 %	20 %	40 %	VS

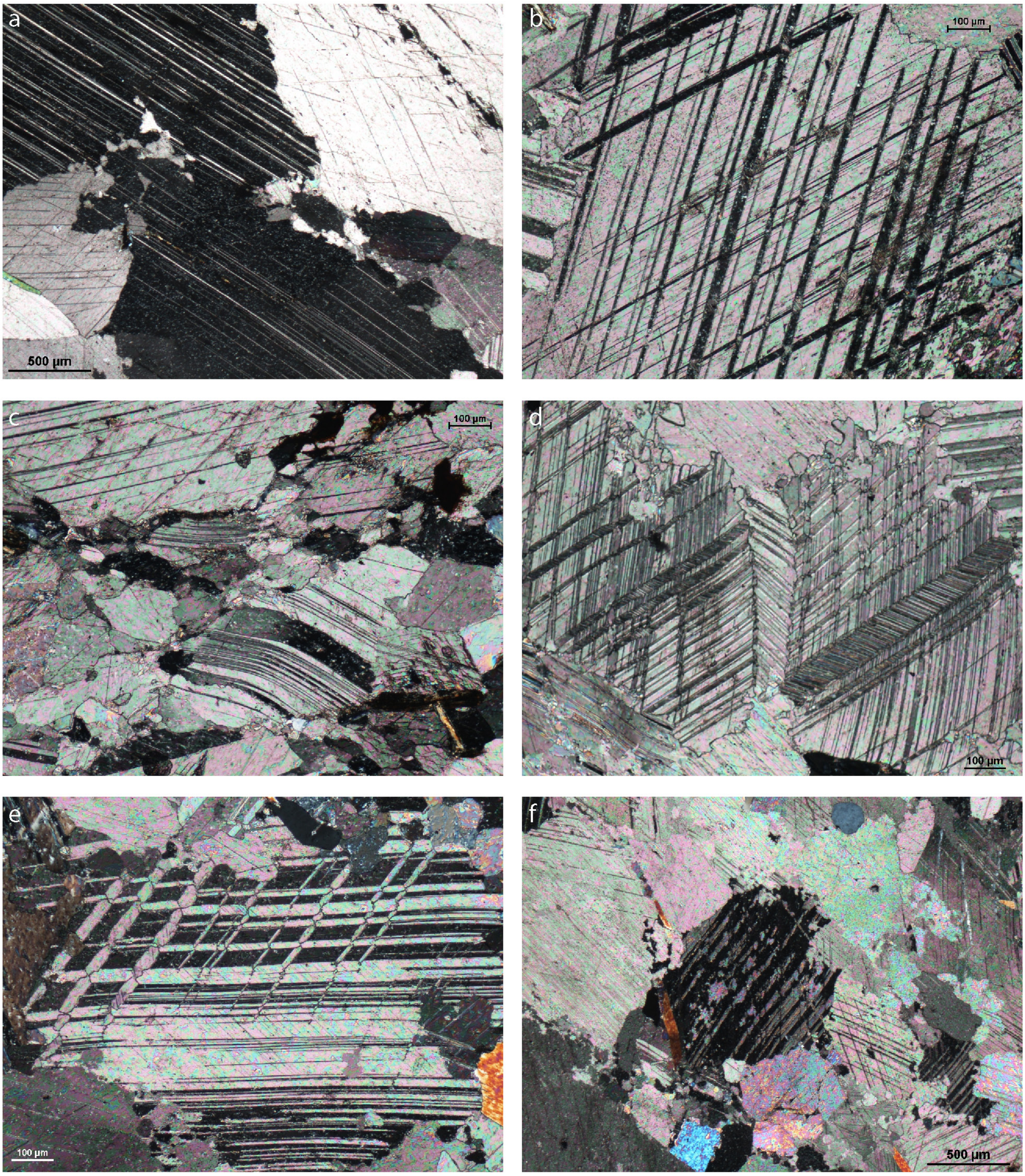

Fig. 7. Representative examples of twin patterns from Pohorje samples: (a) thin straight twins of Type I; three sets of twins may be recognized in the grain on the lower left and upper right; (b) two sets of thick straight twins of Type II; (c) curved and tapered thick twins of Type III; (d) twinned twins of Type III; thin straight twins developed within thick twin lamellae; (e) thick lensoid twins of Type III; thin straight twins within thick lamellae are visible; (f) thick patchy twins in of Type IV "NE–SW" direction with irregular – sutured boundaries that formed most probably due to grain boundary migration processes postdating twinning (Burkhard, 1993).

twins (> 5 µm) of Type II are the main deformation twin type in six localities (Table 1). They are accompanied by minor amount of twins of Type I and/or Type III. They are perfectly straight, parallel and frequently developed in several sets with different orientation (Fig. 7b). Type III twins are the dominant type of deformation pattern in the majority of the investigated marble samples. Sixteen out of twenty-five localities are characterized by different shapes of curved, tapered and lensoid thick twins of Type III (Fig. 7c-e, Table 1). The nods in lensoid twins are indicating the start of the recrystallization process. One of the characteristics of the Type III twins is the de-

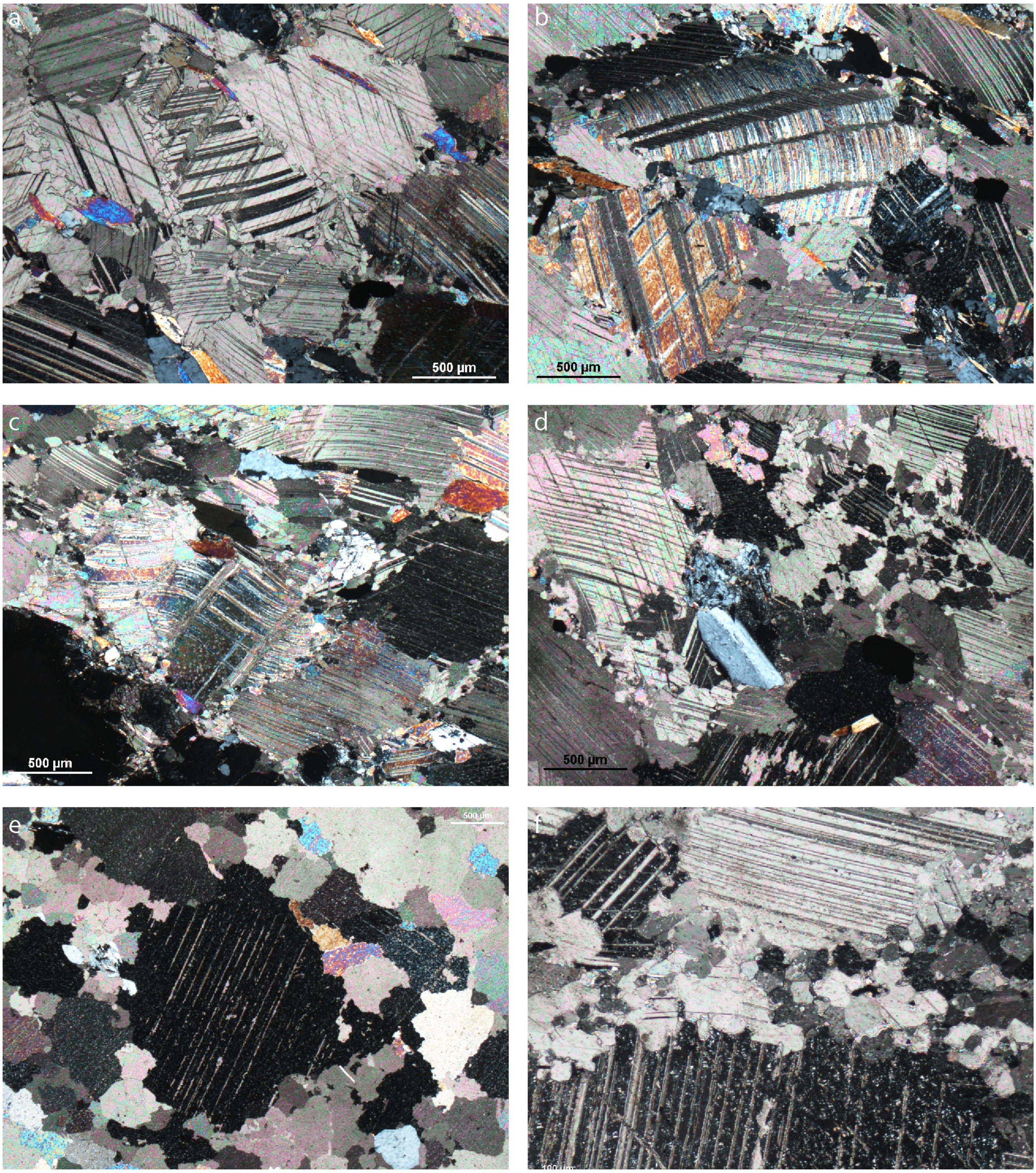

Fig. 8. Type III thick twins of various shapes (curved, tapered, twinned, lensoid) and Type IV twins are accompanied with the increasing degree of recrystallization along grain boundaries following from figure (a) to (e). Deformation twins in recrystallized calcite grains (f).

velopment of twinned twins expressed as thin straight twins within thick twin lamellae (Fig. 7d, e). Type IV twins prevail at only two localities (Surč - Site No. 143 and Gorenje 3 - Site No. 172 in Table 1 and in Fig. 6). These thick patchy twins show irregular, sutured boundaries modified by dynamic recrystallization due to grain-boundary migration (Fig. 7f). They are often found as complementary type of twins at localities where Type III twins are the dominant deformation pattern. They are absent in samples where twins of Type I and II are prevailing (Table 1).

With increasing dominance of Type III (and Type IV) twins the recrystallization along grain boundaries becomes very pronounced. Initially, a single line of small individual untwined calcite crystals forms along big twinned calcite grains (Fig. 8a, b) producing extremely irregular grain boundaries. With increasing deformation and recrystallization, increasingly larger parts of the grains become recrystallized, and former deformed large grains are replaced by smaller undeformed calcite grains (fig. 8c–e). In few locations, the second generation of deformational twining was observed in the form of mechanical twins of Type I starting to develop in recrystallized calcite grains (fig. 8f).

From the study of the twin pattern abundance in Pohorje marbles we deduce that the prevailing type of e-twinning are twins of Type III, which correspond to the temperature of deformation exceeding 200 °C. Thick twins do not show signs of grain boundary recrystallization, therefore we interpret that twinning developed during temperature decrease due to exhumation.

Conclusions

Marbles from Pohorje are mostly pure calcitic marbles and only rare examples with calcitic-dolomitic compositions were encountered. Calcite (and dolomite) represent 95 % of the rock, the rest is composed of pyroxenes (diopside), amphiboles (tremolite), olivines (forsterite), quartz, feldspars (potassium feldspars and plagioclases), epidote, zoisite, vesuvianite, scapolite, muscovite, biotite, phlogopite, rare grains of titanite, rutile, zircone, apatite, small ferric oxides and sulfides, chlorite after biotite and serpentine minerals replacing olivines.

All four known types of mechanical e-twins are present in calcite whereas dolomite crystals are undeformed and show no signs of twinning. Type III twins are the dominant type of deformation pattern, followed by Type II twins. Type I and Type IV twins are very rare. Type IV twins are never found in localities where twins of Type I and II are dominating. Twinning in Pohorje marbles occurred above 200 °C and was followed by a decrease of temperature during exhumation.

In samples with Type III and IV twins recrystallization becomes an important process. Small individual untwined calcite crystals along grain boundaries are progressively replacing bigger calcite grains. Second generation of e-twining was observed in form of Type I twins develop in recrystallized calcite grains.

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