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'High-temperature' texture in naturally deformed Carrara marble from the Alpi Apuane, Italy

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Abstract

From deformation experiments and numerical modelling, a large type variety of crystallographic preferred orientations (textures) are known for calcite. In contrast, naturally deformed samples usually show the 'low-temperature (LT)'-texture type with only minor texture variations. The 'high-temperature (HT)'-texture type is rarely described and mostly not very well defined. Based on neutron diffraction measurements and a quantitative texture analysis by means of the iterative series expansion method and the texture component model, this study gives evidence for the HT-texture type in a deformed marble from the Alpi Apuane in Italy. The microstructure of the sample shows elongated grains with long/short axis ratios of up to 10:1. The long axes of the grains are oriented parallel to the general direction of transport indicating prolate strain, but no shear sense. From the texture, a shear sense can be deduced that cannot be fully brought in line with the regional deformation and thermal history. The results indicate a larger texture variety of naturally deformed calcite rocks than generally assumed. This should stimulate further systematic texture studies for a better understanding of the texture forming mechanisms and the closely connected understanding of the kinematic significance of textures for the analysis of regional deformation histories.

Keywords: Naturally deformed calcite; Texture; Microstructure; Carrara marble; Alpi Apuane

1. Introduction

In deformed rocks, different patterns of crystallographic preferred orientations (texture-types) can be indicators for deformation conditions and deformation mechanisms. The determination of textures can help to unravel deformation histories. In this context, the measurement of calcite textures is of particular interest because: (1) calcite rocks often play a key role during orogenesis as weak layers accomodating nappe emplacements, (2) they occur as monophase layers of considerable thickness (e.g. carbonate platforms), and (3) they are easily deformable at relatively low temperatures both in nature and the laboratory. Therefore, calcite is very suitable for deformation experiments. Numerous such deformation experiments provide a rather good knowledge of the deformation mechanisms of calcite (e.g. Wagner et al., 1982; Kern and Wenk, 1983; Schmid et al., 1987; Rutter et al., 1994; Rutter, 1995; review in De Bresser and Spiers, 1997; Pieri et al., 2001a,b and references therein). However, direct comparisons of natural versus experimentally induced textures are rare.

For calcite textures, deformation experiments and numerical texture simulations in pure shear and simple shear (Wenk et al., 1986, 1987) have given evidence for the existence of 'low-temperature (LT)' and 'high-temperature (HT)' texture-types (Fig. 1). This can be explained by texture transitions due to the temperature dependence of the critical shear stresses of different intracrystalline slip systems (review in De Bresser and Spiers, 1997). These experiments and simulations have shown that calcite textures depend upon the ratio between simple and pure shear and the amount of shear. Particular calcite deformation experiments also show different textures for, e.g. different temperatures and shear strains in simple shear (Schmid et al., 1987), in compression and extension (Rutter et al., 1994) or for torsion deformation experiments (Pieri et al., 2001a,b). Furthermore, their results show different

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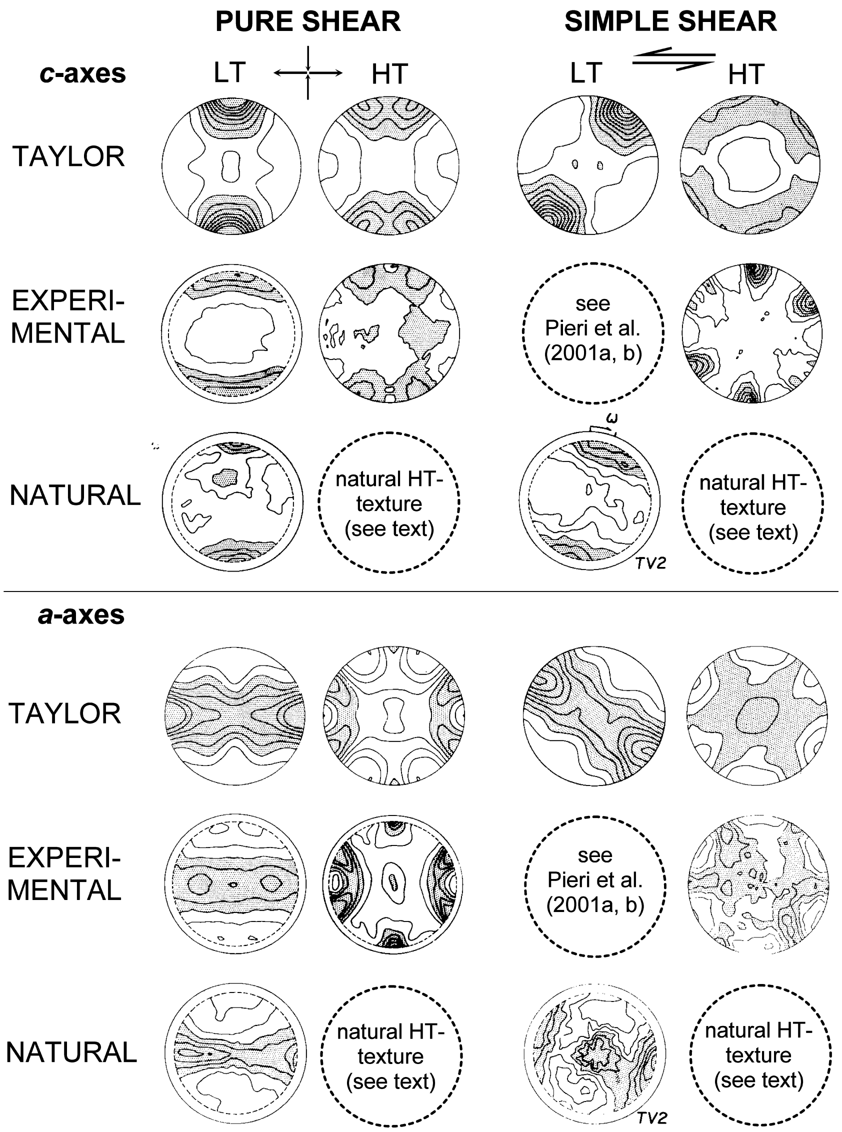


Fig. 1. Compilation of calcite textures for different deformation regimes and temperature ranges from the literature (after Wenk et al., 1987). Note the missing natural HT-texture types. The textures are represented by pole figures of the *c*(0001)- and $a\langle\bar{1}\bar{1}20\rangle$-axes (equal area projection, contour interval is 0.5 m.r.d. except for TV2, where it is 0.1 m.r.d.; the lowest contour interval is 0.5 m.r.d., shaded above 1 m.r.d.; for the *a*-axis pole figures the contour intervals are 0.25 m.r.d.).

texture types for intracrystalline slip and dynamic recrystallization.

This large variety of texture types is in contrast to the small texture varieties found in nature. Wenk et al. (1987) and Lafrance et al. (1994) stated that naturally deformed calcite shows barely differentiated simple *c*-axis maximum for different deformation regimes, i.e. for a wide range of temperature, strain rate and grain size. The HT-texture type, especially, has been rarely described in the literature (De Bresser, 1989; Burlini et al., 1998; Kurz et al., 2000) and is not always clearly defined, as will be discussed further later. This paper presents a HT-texture type of a naturally deformed Carrara marble and discusses its methodical and geological implications.

2. Geological setting of the Alpi Apuane and sample location

The sample investigated was collected in the marble quarries of the Carrara area in the Alpi Apuane of the Northern Apennine in Italy (Fig. 2). Generally, the Carrara marbles are famous due to their widespread utilization for statues and building stones. In structural geology, the Carrara marbles are well-known from their usage as a starting material for deformation experiments (e.g. Schmid et al., 1980; Rutter et al., 1994; Pieri et al., 2001a,b). Recent investigations address the relationship between fabric characteristics and weathering mechanims (e.g. Barsotelli et al., 1999; Weiss et al., 1999; Leiss and Weiss, 2000).

The Alpi Apuane (Fig. 2) represents a tectonic window

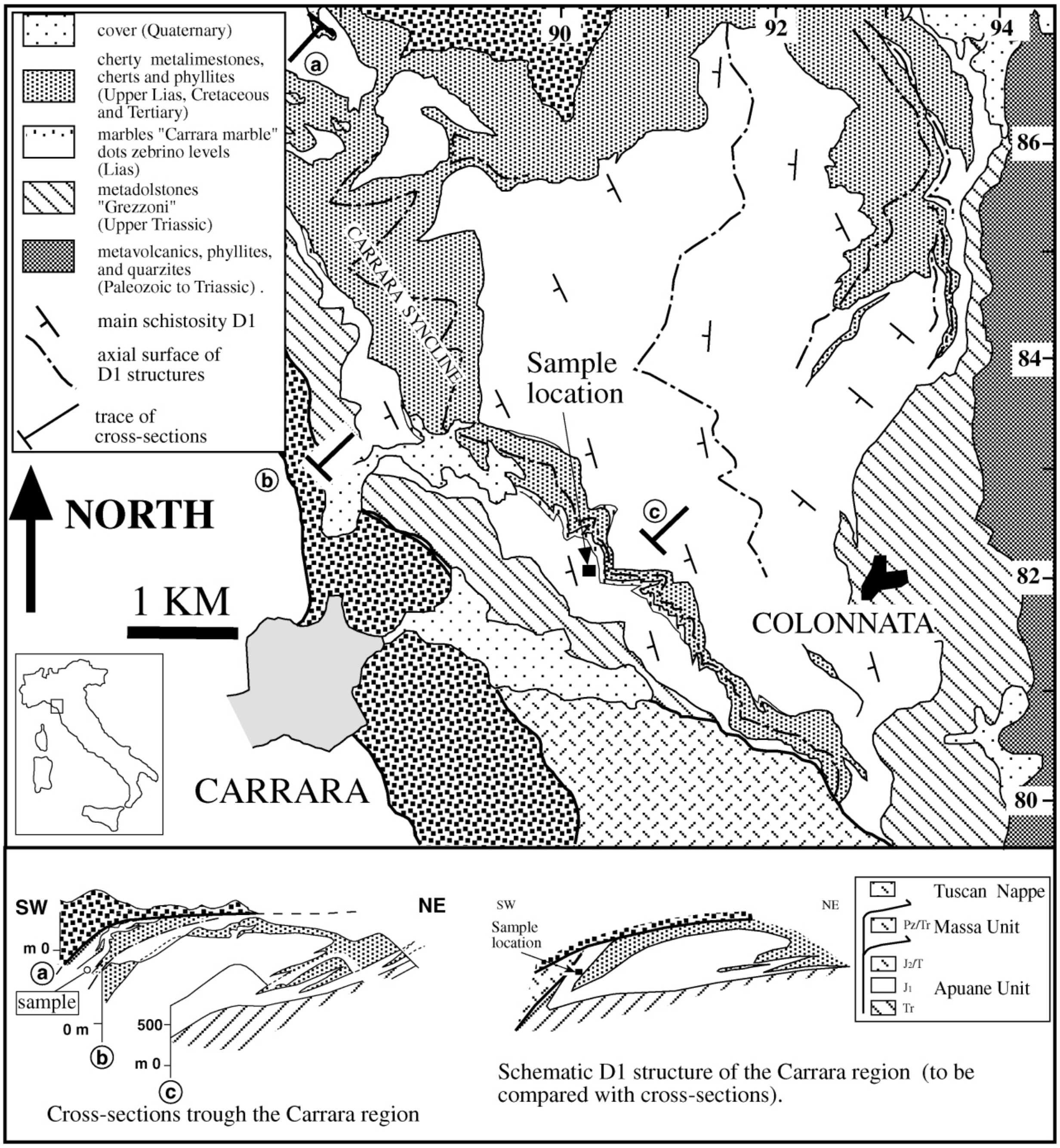


Fig. 2. Geological setting and sample location (map modified after Carmignani and Kligfield, 1990).

where the lowermost units of the inner side of the Northern Apennine are exposed (Elter, 1975; Carmignani et al., 1978 and references therein). Below the nappe system, which is mainly composed of ophiolite-bearing Liguride units, the continental-derived Tuscan units are exposed.

In the area studied, the lowermost Tuscan unit is respresented by the Apuane Unit (Fig. 2), which is composed of a Triassic to Oligocene metasedimentary sequence and an unconformably overlain Hercynian basement (Conti et al., 1993; Molli et al., 2000b and references therein).

The deformation history of the Apuane unit is characterized by Late Oligocene–Early Miocene continent–continent collision and subsequent exhumation within an extensional strain regime at regional scale affecting the inner side of the Northern Apennine (Carmignani and Kligfield, 1990; Jolivet et al., 1998; Molli et al., 2000b and references therein). During these two main tectono-metamorphic events (D1 and D2; Carmignani and Kligfield, 1990; Molli et al., 2000a), characteristic deformation structures at regional and macroscopic scale developed. The contractional D1-event (ca. 27–20 Ma; Kligfield et al.,

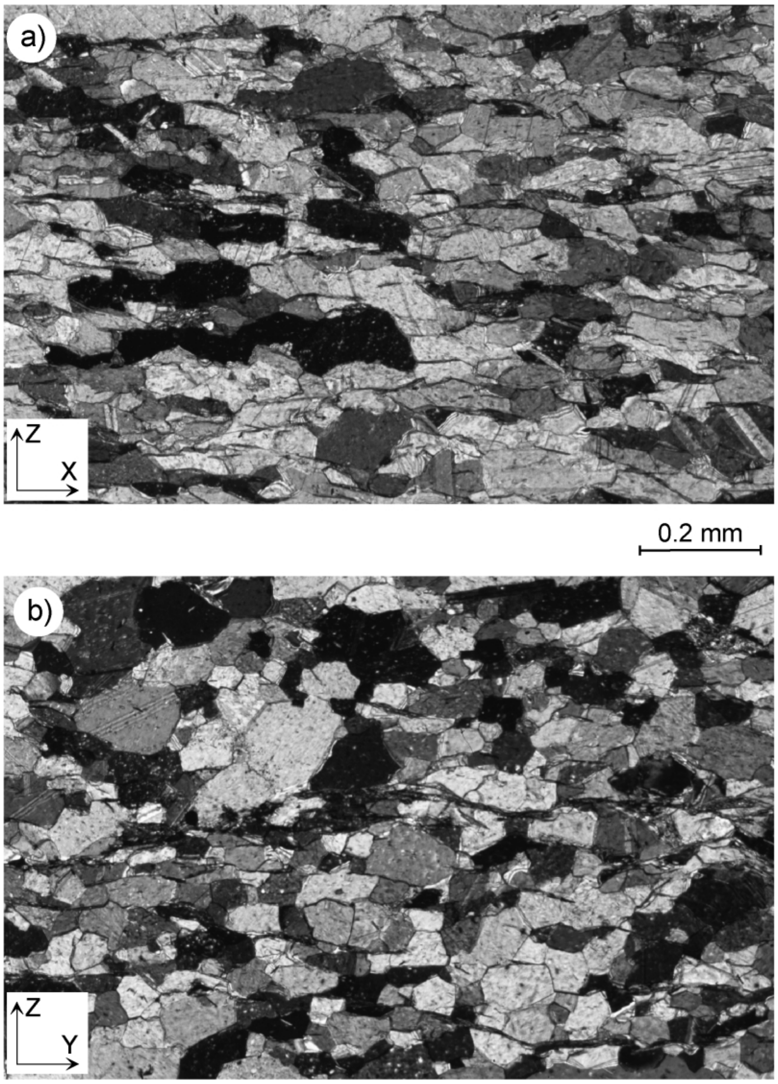


Fig. 3. Photomicrographs of the microstructure in polarized light. Orientation of thin sections: (a) normal to the foliation/parallel to stretching lineation (*XZ*-section), (b) normal to the foliation/normal to the lineation, i.e. parallel to the fold axis (*YZ*-section).

1986) resulted in nappe formation and nappe emplacement, which took place under upper greenschist facies conditions.

Large scale (e.g. the Carrara syncline) and small scale, NE-vergent folds and the main regional schistosity developed. Under the retrograde metamorphic conditions of D2, the D1-folds and the main schistosity were homoaxially overprinted. During the uplift, the deformation conditions continuously changed from a ductile to a brittle environment (Ottria and Molli, 2000). The syn-metamorphic deformation came to an end at about 10–8 Ma ago (Giglia and Radicati di Brozolo, 1970; Kligfield et al., 1986).

The greenschist facies metamorphic conditions of the Apuane unit are indicated by chlorite and biotite-rich zones. Al-silicates of the pyrophyllite + quartz zone indicate a maximum temperature between 350 and 450 °C and a maximum pressure of about 4–6 kbar (Franceschelli et al., 1997; Jolivet et al., 1998; Molli et al., 2000b). The thermal peak of metamorphism was attained during D1. In the sample location area, a temperature of 430–450 °C was reached (calcite/dolomite geothermometer; Molli et al., 2000a).

The sample was collected in a small abandoned quarry about 100 m NE of the Ponti di Vara between Miseglia and Fantiscritti (UTM kilometric grid 8212/9350, IGM sheet 96). The quarry is situated in the inverted limb of the N–S-striking, E-vergent, tight to isoclinal Carrara syncline (Fig. 2). Stratigraphically, the sample comes from the Zebrino levels, which are interposed between Jurassic marbles and late Jurassic cherty metalimestones.

3. Results

3.1. Microstructure

The sample from the yellowish marbles of the Zebrino levels (Fig. 2) exhibits a well-developed foliation (dip direction 53 → 230°) and a strongly developed SW-dipping

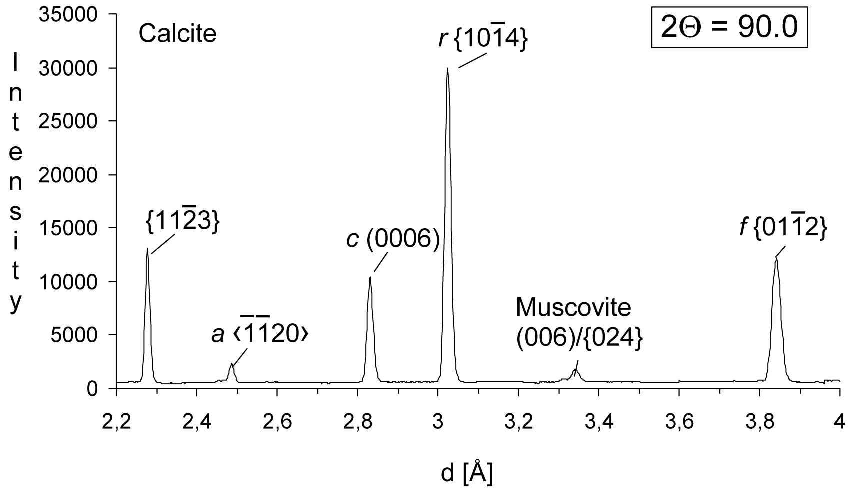


Fig. 4. Averaged and normalized summation of all 1368 time-of-flight spectra. Indicated calcite peaks are used for the quantitative texture analysis.

stretching lineation. Macroscopically, the foliation is defined by micas preferentially oriented parallel to the foliation plane as well as by alternating layers consisting of phyllosilicate-poor, coarse-grained calcite and phyllosilicate-rich, fine-grained calcite. No clear shear sense indicators can be observed at mesoscopic scale.

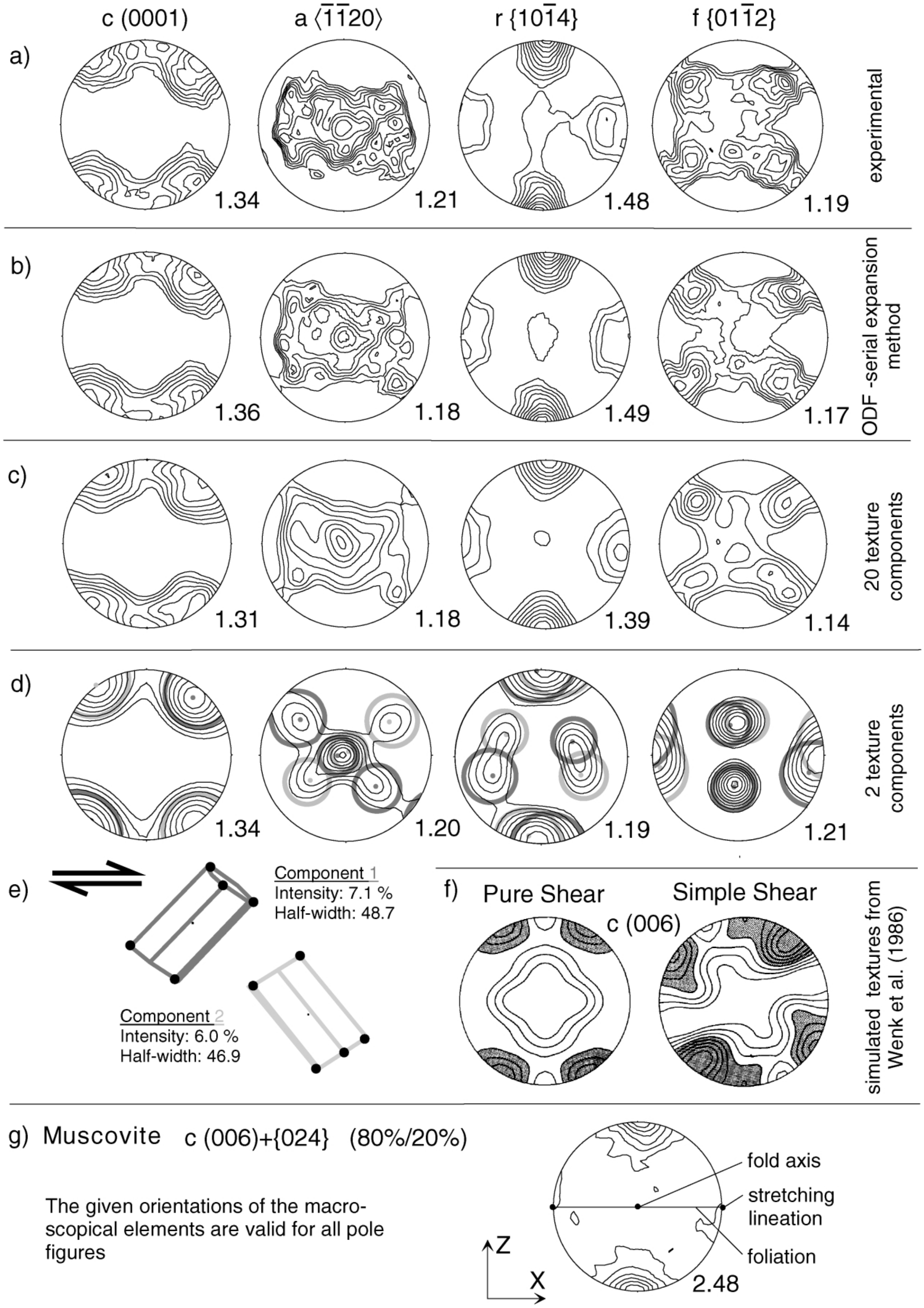
Microscopically, the section normal to the layering and parallel to the lineation (*XZ*-section, Fig. 3a) shows elongated calcite grains with aspect ratios up to 10:1 and long axes ranging from about 0.2 mm in the fine-grained to about 2 mm in the coarse-grained layers. On average, the long axes are oriented parallel to the stretching lineation. An oblique grain shape fabric is missing, so a shear sense cannot be deduced.

In the section normal to the foliation and normal to the stretching lineation (*YZ*-section), no or only a very weak foliation-parallel elongation can be observed (Fig. 3b). From these two-dimensional microscopical grain shape observations, a three-dimensional prolate grain shape can be deduced. This distinctive grain shape anisotropy correlates and explains the pronounced macroscopical stretching lineation, which is especially visible on weathered surfaces. In both sections, the grain boundaries are straight or curved. Twins are rare and subgrain formation is absent. The micas are oriented parallel to the main foliation and a shear sense cannot be deduced.

3.2. Quantitative texture analysis

Due to the predominantly large grain size, neutron diffraction was applied to obtain a statistically reliable bulk texture of the sample. This is a precondition for further investigations like the correlation of the texture with anisotropic physical properties (e.g. Leiss and Ullemeyer, 1999; Weiss et al., 1999; Leiss and Weiss, 2000). Using the texture diffractomater SKAT (Ullemeyer et al., 1998) at the pulsed reactor IBR-2 in Dubna (Russia), a spherical sample with a diameter of 30 mm was measured. A measuring grid close to a regular 5° × 5° grid (Ullemeyer et al., 1998), an exposition time of 15 min per sample position and the simultaneous application of 19 detectors resulted in a total measuring time of 18 h. From the time-of-flight spectra (Fig. 4), the experimental pole-figures $c(0006)$, $a\langle\bar{1}\bar{1}20\rangle$, $r\{10\bar{1}4\}$, $f\{01\bar{1}2\}$ and $\{11\bar{2}3\}$ were extracted (Fig. 5a). On the basis of these pole-figures, a quantitative texture analysis (QTA) was carried out by calculating the orientation distribution function (ODF) by means of the iterative series-expansion method, including the positivity condition (Dahms and Bunge, 1988, 1989). Due to the simple texture and the weak pole-figure maxima, a series-expansion degree of $L = 22$ was considered to be sufficient for a reliable texture reproduction. Additionally, a quantitative description of the texture was carried out by fitting the experimental pole-figures with Gaussian-shaped texture components (Helming and Eschner, 1990). The results of both methods are displayed in Fig. 5b and c. All pole-figures, which are relevant for the interpretation or the evaluation of the deformation mechanisms, were plotted (compare, e.g. with Leiss and Barber, 1999; Pieri et al., 2001a,b). Pole-figures of the weak but distinct texture are projected in a plane normal to the foliation and parallel to the stretching lineation. The $c(0001)$-axis pole-figure shows two maxima that are inclined about 50° to the foliation normal. The very broad $a\langle\bar{1}\bar{1}20\rangle$-axis maximum is low in intensity and oriented normal to the stretching lineation, i.e. parallel to the fold axis. In the $r\{10\bar{1}4\}$-pole-figure, three maxima can be observed: a strong maximum parallel to the foliation normal, a moderate maximum parallel to the stretching lineation and a very weak maximum parallel to the fold axis. The $f\{01\bar{1}2\}$-pole-figure exhibits a cross girdle distribution with an intersection oriented parallel to the fold axis.

Due to the low volume fraction of muscovite, only the experimental $(006) + \{024\}$ pole-figure could be measured (Fig. 5g). Therefore, a QTA of muscovite is not possible. Since the intensity contribution of $\{024\}$ is only about 20% of the bulk peak intensity and the $\{024\}$-planes are


c (0001)
a ⟨$\bar{1}1\bar{2}0$⟩
r {$10\bar{1}4$}
f {$01\bar{1}2$}
a)
experimental
1.34
1.21
1.48
1.19
b)
ODF -serial expansion method
1.36
1.18
1.49
1.17
c)
20 texture components
1.31
1.18
1.39
1.14
d)
2 texture components
1.34
1.20
1.19
1.21
e)
Component 1
Intensity: 7.1 %
Half-width: 48.7
Component 2
Intensity: 6.0 %
Half-width: 46.9
f)
Pure Shear
Simple Shear
c (006)
simulated textures from Wenk et al. (1986)
g) Muscovite c (006)+{024} (80%/20%)
The given orientations of the macro-scopical elements are valid for all pole figures
fold axis
stretching lineation
foliation
Z
X
2.48

differently oriented to the (006)-planes, the pole-figure gives a general idea of the orientation of the basal planes, which are oriented parallel to the foliation plane.

4. Discussion

4.1. Comparison of the texture with textures from deformation experiments and texture simulations

Comparing our results with those from the literature on plane strain texture simulations and deformation experiments (see Fig. 1) and following the nomenclature of Wenk et al. (1987), the texture of our sample can be classified as 'HT-texture-type': the *c*-axis distribution shows the characteristic double maximum with the bisecting line normal to the shear/flattening plane and the *a*-axis distribution displays an adequate broad *a*-axis maximum normal to the shear direction. The question arises whether the deformation conditions like temperature, strain rates, pure shear or simple shear can be evaluated from the texture, and if it is possible to determine the ratio between simple shear and pure shear, as demonstrated by Wenk et al. (1987, Fig. 12) for LT-textures (Ratschbacher et al., 1991).

At pure shear and HT-conditions, texture simulations on the basis of the Taylor theory (Wenk et al., 1986, 1987) show two *c*-axis maxima with the same intensity and the same angle between the maxima and the shear plane/flattening normal (Figs. 1 and 5f). At simple shear and HT-conditions, the intensity maxima and angles are different. The stronger maximum is significantly rotated against the shear sense, i.e. the angle between the maximum and the foliation normal is increased by about 15°. In Wenk et al. (1986) the weaker maximum is slightly rotated with the shear sense, the angle between the maximum and the foliation normal is increased by about 35° (Fig. 5f). In Wenk et al. (1987) the weaker maximum is found in a similar postion as in pure shear (Fig. 1). The reasons for the differences between the texture simulations in Wenk et al. (1986, 1987) cannot be clearly reproduced from the literature. In both cases, however, the total distance between the two maxima is increased and the bisecting line between the two maxima is not normal to the foliation plane but rotated with the shear sense. Especially the *c*-axis pole-figures show orthorhombic symmetry for pure shear and monoclinic symmetry for simple shear conditions.

At first glance, the texture of our sample looks like a HT-texture developed in a pure shear regime. In detail, however, a weak inclination of the bisecting line between the two *c*-axis maxima in respect to the foliation as well as slightly different intensities for the two maxima reveal the characteristics of a HT-texture developed in simple shear. These characteristcs are evident, regardless of whether one looks at the maximum intensities in the experimental pole-figures or the maximum intensities in the recalculated pole-figures (Fig. 5). The idea of applying only the two main components for the texture description (Fig. 5d and e) allows a semi-quantitative approach to the description of the texture asymmetry by determining maxima intensities and angles between maxima and foliation normals. As demonstrated in Wenk et al. (1987, Figs. 11 and 12) for LT-textures, these values are the basis for an estimation of the amount of shear and the ratio between pure and simple shear. At present, we can only assume a weak simple shear component, because transition types between simple and pure shear have not yet been modelled for HT-textures. In contrast to the *c*-axis pole-figure, simple shear is more evident in the *a*-axis pole-figure (compare Figs. 1 and 5). Unfortunately, only *c*-axis pole-figures are usually shown in the literature. For a more reliable comparison of textures, future results from simulations should also display further characteristic pole-figures like the $\{10\bar{1}4\}$-pole-figure with its typical submaxima (compare e.g. Leiss and Ullemeyer, 1999; Pieri et al., 2001a,b). Such pole-figures show more complex patterns, which allow much better discriminations between texture types.

Recent torsion deformation experiments of Carrara marble (Pieri et al., 2001a,b) provide excellent new data on the understanding of the microstructural and textural development of calcite during deformation. They present microstructures and textures for different shear strains and temperatures of 1000 and 1200 K. A very good fit to the microstructure and texture of our sample is found for $\gamma = 2$ and $T = 1000$ K. At higher shear strains, the authors found a characteristic recrystallization texture that also shows two main texture components but with maxima rotated about 90° with respect to the shear plane normal. For our sample, these results argue for a deformation texture at high temperatures.

Fig. 5. High-temperature textures of calcite in naturally deformed marbles from the Zebrino levels of the Carrara-syncline: (a)–(c) equal area projection, lowest contour equal to 1.0 multiples of random distribution, the relative maxima are given, (d) as (a)–(c) but stereographic projection, (e) equal area projection, contour intervals are 0.25 m.r.d., shaded above 1.25 m.r.d.). (a) Experimental pole-figures from neutron diffraction. (b) Pole-figures recalculated from the iterative series expansion method. (c) Pole-figures recalculated from 20 texture components. Only six components show a relevant intensity of >1% (in brackets: half widths): 8.12% (56°), 8.09% (53°), 2.43% (36°), 2.07% (35°), 1.53% (31°), 1.53% (31°), Fon (randomly oriented portion): 71%. (d) Pole-figures recalculated from a component fit for the two strongest components. The circles indicated within the pole figures represent the half-widths of the components and the spots inside these circles indicate the orientation of the normal to the corresponding {hkil} of the single crystals (compare with (e), left). (e) Orientations of the two main components (see (d)) are illustrated by crystals representing the hexagonal (valid in case of diffraction data) symmetry of calcite. The intensity difference between the two components is about 15%. (f) *c*-axis pole figures from numerical modelling (Wenk et al., 1986). For simple shear, the intensity difference of the two maxima is about 9%. (g) Experimental pole-figure of muscovite. The given orientation of the pole-figure in respect to the regional structural elements is valid for all pole figures of this figure.

The experimentally developed microstructure shows an oblique grain shape fabric with respect to the shear/flattening plane and a bisecting line between the two *c*-axis maxima rotated against the shear sense. This supports the interpretation of dominant pure shear for the development of our sample. Based on the viscoplastic model, the authors also present texture simulations, but not for the HT-texture type.

4.2. Comparison of the texture with other natural calcite HT-textures

De Bresser (1989) presents *c*-axis pole-figures of calcite from the Gavarnie thrust zone in the central Pyrenees. The measurements were carried out by means of the universal stage considering up to 200 grains per sample. De Bresser (1989) classified some of the *c*-axis distributions as HT-textures. However, separated maxima are not clearly visible and the patterns can also be interpreted as incomplete girdle distributions.

Kurz et al. (2000) presented *c*- and *a*-axis pole-figures recalculated from quantitative X-ray texture analyses of samples from the Tauern Window, Eastern Alps. Some textures are classified as HT-texture types. However, the differences between the LT- and HT-textures are not very clear. Due to the mainly coarse-grained samples, the grain statistics in the X-ray experiment is rather poor. This causes scraggly pole-figures with single grain peaks. Smoothed pole-figures would probably show minor differences between the textures in a more clear way. This argument is also supported by the *a*-axis pole-figures, which give no clear indication for a classification of LT- and HT-textures. On the basis of the data of De Bresser (1989) and Kurz et al. (2000), a semi-quantitative discussion on the comparison with the experimental and simulated textures is difficult.

Burlini et al. (1998) present pole-figures for the *c*-axis and *e*-twin-plane distributions from the Splügenpass, central Alps. Data were measured by means of the U-stage. At least two samples show two clearly seperated *c*-axis maxima and can be classified as HT-textures. Since the paper focuses on the anisotropic physical properties of the samples, the authors did not classify LT- and HT-textures and did not discuss details on deformation mechanisms and deformation conditions in view of texture types.

4.3. Relation of the texture to the deformation history

According to Carmignani et al. (1978) the Carrara syncline as well as the other D1 structures in the Alpi Apuane were formed during passive folding within a general NE-directed simple shear regime. Our data hardly fit in such a model since the texture suggests a general non-coaxial flow with a large component of coaxial deformation. Moreover, the shear sense derived from the texture suggests a downward movement of the hanging wall towards the SW. This is contrary to the expectations of the regional model.

Nevertheless, the deformation regime inferred from the texture is in agreement with more recent structural data (Molli et al., 2000a,b). These data suggest an antiformal stack phase at the end of the D1-history, associated with a large component of coaxial strain.

The downward movement, however, is not in agreement with the dominant NE-directed shearing during the D1-history. An alternative interpretation of the downward movement could be the relation of the texture development with the D2-extensional deformation, which is associated with a general top-to-SW directed movement within the studied area. This explanation, however, appears unlikely because: (1) the high strain zones in the zebrino levels are subsequently folded by a large scale D2-event, and the fabric should have formed during D1-history; (2) it is assumed that the temperature peak had been already exceeded during D2-deformation and furthermore, the microstructural features of the D2-overprinting are different (Molli et al., 2000a,b).

Since our inferences are based only on one sample, further kinematic interpretations are not reasonable. Only additional systematic texture analyses in relation to the fold geometry and to the temperature profile will allow us to learn more about the significance of calcite textures as a tool for unravelling the deformation history. This should be done also in view of the question, which parameters like differential stress, temperature, strain rate, grain size etc. primarily control the development of a certain LT- or HT-texture type (compare with Pieri et al., 2001a,b).

5. Conclusions

The calcite texture presented in this study indicates the existence of the numerically and experimentally predicted HT-texture type for naturally deformed Carrara marble. To deduce deformation conditions by quantitatively comparing the natural texture with textures from experiments and texture simulations, statistically representative texture measurements are required for the coarse-grained marbles. For this goal, neutron diffraction is a very suitable tool since large sample volumes can be investigated to overcome the restriction of large grain sizes.

Our results and the results from Burlini et al. (1998), De Bresser (1989), Leiss and Ullemeyer (1999), Leiss and Weiss (2000) and Kurz et al. (2000) demonstrate a greater diversity of texture-types in naturally deformed calcite as it was assumed in Wenk et al. (1987) and Lafrance et al. (1994). This insight and new experimental results of Pieri et al. (2001a,b) should stimulate new texture simulations based on the viscoplastic model (e.g. Kocks et al., 1998) and more detailed and quantitative analyses of natural structures in marbles to learn more about the correlation between texture types, microstructures and deformation mechanims, deformation conditions and deformation regimes. Such studies will help to evaluate the applicability of calcite textures for analyses of deformation structures and regional deformation histories.

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