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Determination of deviatoric stress tensors based on inversion of calcite twin data from experimentally deformed monophase samples: preliminary results

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Abstract

Following previous successful (paleo)stress determinations from numerically generated aggregates and naturally deformed samples, preliminary results about stress reconstructions based on inversion of calcite twin data from experimentally deformed monophase samples are reported. This new study carried out on samples of Carrara marble and crinoidic limestone from eastern France provides a test of the validity of stress reconstructions using inverse methods, which had not been properly calibrated before. The percentages of correlated twins are discussed for each stress tensor, and the range of uncertainties on the determination of stress orientations and differential stress magnitudes is evaluated.

1. Introduction

Since the work of Turner (1953), it is known that the analysis of the geometry of twinning in calcite grains may permit the determination of the orientation of the principal stresses responsible for the intracrystalline deformation. Following this pioneering work, various methods for reconstructing paleostress orientations have been suggested and subsequently improved (e.g., Nissen, 1964; Spang, 1972; Dietrich and Song, 1984). The possible use of mechanical twinning in calcite as an indicator of differential stress magnitudes has also been discussed in both theoretical and experimental contexts (Friedman and Heard, 1974; Jamison and Spang, 1976; Tullis, 1980; Spiers and Rutter, 1984; Rowe and Rutter, 1990; Lacombe and Laurent, 1992). Recently, computerized inversion (Laurent et al., 1981, 1990; Etchecopar, 1984) has supported the dynamic analysis of calcite twinning and its interpretation in terms of stress.

In the last five years, many authors have reported successful reconstructions of regional paleostress orientations based on the inverse analysis of twin sets in natural carbonate samples (e.g., Larroque and Laurent, 1988; Tourneret and Laurent, 1990; Lacombe et al., 1990, 1992). Simultaneously, differential stress magnitudes were calculated from these twin sets based on the assumption of a constant yield stress value for twinning, thus permitting first estimates of stress levels prevailing in the rock masses during the reconstructed tectonic events. However,

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these methods of stress determination have not been calibrated in the laboratory despite some efforts to calibrate them with paleodepth estimates and rock mechanics data (Lacombe and Laurent, 1992); accordingly, uncertainties in the results, especially in differential stress magnitudes, remained unknown. To this respect, despite numerous experiments about deformation of calcite aggregates carried out during the last decade (e.g., Spiers and Rutter, 1984; Schmid et al., 1987; Rowe and Rutter, 1990; De Bresser, 1991), it appeared necessary to perform some new experiments aiming at evaluating the validity and the range of uncertainties of the determination of differential stress magnitudes based on inversion of calcite twin data.

2. Geometry and occurrence of mechanical twinning in calcite

Twin lamellae are a common microscopic feature in calcite (Handin and Griggs, 1951; Turner et al., 1954; Friedman, 1964). A twin lamella results from an approximation to simple shear of part of the host crystal along specific crystallographically defined planes, in such a way that the resulting twinned portion of the crystal bears a mirrored crystallographic orientation to the untwinned portion across the twin plane (Fig. 1). At low pressure and temperature, calcite aggregates deform primarily by twinning on e $\{01\bar{1}2\}$ planes. In thin section, the resulting e twin lamellae are straight and very thin (about a fraction of micron). Each crystal contains three potential e twin planes which are arranged symmetrically around the C-axis.

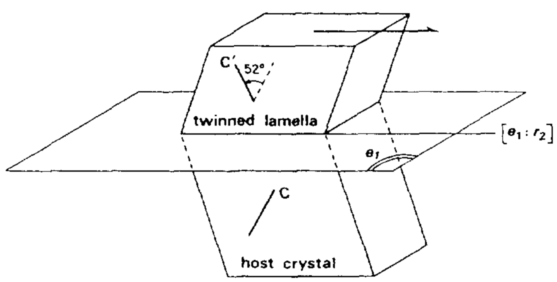

Fig. 1. Schematic sketch of a twin lamella $\{01\bar{1}2\}$ in a calcite crystal. The e twin plane is horizontal and perpendicular to the plane of drawing. C and C' are the crystallographic C-axes of the host grain and the twinned lamella, respectively. The twinning direction $[e_1:r_2]$ corresponds to the direction of motion of the part of the crystal located above the twin plane. The imposed sense of shear is indicated by the arrow.

In contrast to most intracrystalline slip systems, twinning in calcite is a deformation mechanism with no temperature and normal stress dependence (e.g., Wenk et al., 1983; Burkhard, 1993). Twinning requires a resolved shear stress τ_s (the component of applied stress along the twinning direction) that exceeds a critical value τ_a. This critical value is nearly independent on temperature, confining and fluid pressures, but does depend on grain size (Olsson, 1974; Rowe and Rutter, 1990). Experiments carried out between 25°C and 800°C show that the critical resolved shear stress calculated at 3% strain varies between 15 MPa (at 25°C) and 9 MPa (at 300°C), and remains approximately 9 MPa at 800°C (Griggs et al., 1960; Turner and Heard, 1965; Tullis, 1980). This has led several authors to propose a nearly constant critical value of 10 MPa (Friedman, 1967; Tullis, 1980; Laurent, 1984), which has been adopted in recent papers (e.g., Laurent et al., 1990; Lacombe and Laurent, 1992; Craddock et al., 1993). In this paper, because our samples display an almost homogeneous grain size of 200–400 μm and were deformed at nearly 3% strain, we also adopted a constant critical shear stress of 10 MPa.

Calcite twinning thus occurs at room temperature, under very little confining pressure and at very low differential stresses, so that its analysis is appropriate for determining paleostresses from non-metamorphic, weakly deformed carbonate rocks. In all the samples studied, the strains involved by twinning are generally very low; in contrast to large, non-coaxial deformation, that may lead to clearly incompatible orientations of twins, these small strains can be approximated by coaxial conditions, so that calcite twins can reasonably be interpreted in terms of stress.

3. Inverse method

The method used herein to determine the deviatoric stress tensor (i.e., principal stress orientations and differential stress magnitudes), is supported by a computerized inversion (Etchecopar, 1984). Assuming homogeneous stress at the grain scale and constant yield stress value for twinning, the inverse problem consists of finding the stress tensor that best fits the distribution of the twinned and the untwinned planes measured in a sample. This tensor must additionally fit the following requirements: (a) $\tau_s \geq \tau_a$ for all the twinned planes (or in practice, for the twinned planes compatible with this tensor, if the twin data set is polyphase); (b) $\tau_s < \tau_a$ for all the untwinned planes.

For simplification of the computerization, the stress tensor solution is searched as a reduced stress tensor such as $(\sigma_1 - \sigma_3)$ is scaled to unity $[(\sigma_1 - \sigma_3)^* = 1]$. The resolved shear stress τ_s acting along any twin plane therefore varies between -0.5 and 0.5, independent of the critical resolved shear stress value.

The first step of the inversion consists of obtaining an initial guess of the solution by applying a number of random tensors. For each tensor, the stress components are calculated for all the twin planes, and these planes are classified according to the (decreasing) resolved shear stress τ_s acting on them. This classification is a useful quality estimator which allows to determine the optimal percentage of twinned planes consistent with the tensor solution.

Because in practice the tensor solution may induce along some untwinned planes a resolved shear stress τ_s greater than that exerted along twinned planes compatible with it, the second step of the inversion process consists of minimizing the function f (ideally equal to 0) defined as:

$$f = \sum_{j=1}^{N} (\tau_{sj} - \tau_{a'}) \qquad (1)$$

where $\tau_{a'}$ is the smallest resolved shear stress applied on the twinned planes compatible with the tensor, and τ_{sj} the resolved shear stresses applied on the N untwinned planes j such as $\tau_{sj} > \tau_{a'}$ (for more details, refer to Etchecopar, 1984; Tourneret and Laurent, 1990). Note that the $\tau_{a'}$ value may thus be considered as the yield stress value for the reduced stress tensor such that $(\sigma_1 - \sigma_3)^* = 1$.

This computerized procedure leads to the stress tensor solution that accounts for the largest number of twinned planes and simultaneously corresponds to the smallest value of f. The orientations of the principal stresses σ_1, σ_2 and σ_3 ($\sigma_1 \geq \sigma_2 \geq \sigma_3$, compression positive) are calculated, as well as of the Φ ratio $[\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3),\ 0 \leq \Phi \leq 1]$ which indicates the shape of the stress ellipsoid. Finally, the actual magnitude of $(\sigma_1 - \sigma_3)$ is easily determined by the equation:

$$(\sigma_1 - \sigma_3) = (\sigma_1 - \sigma_3)^* \cdot \tau_a/\tau_{a'} = \tau_a/\tau_{a'} \qquad (2)$$

τ_a being the actual yield stress value for calcite twinning (e.g., 10 MPa). Then, knowing $(\sigma_1 - \sigma_3)$ and Φ yields the values of $(\sigma_2 - \sigma_3)$ and $(\sigma_1 - \sigma_2)$.

If many twins are found not consistent with the previous stress tensor, the twinned planes consistent with this tensor are withdrawn, and the process is repeated with the residual twinned planes and the whole set of untwinned planes (the untwinned planes should obviously remain untwinned for any tensor). Where polyphase tectonism has occurred, this process may allow separation of superimposed stress tensors, each of them accounting for part of the data; such separation must be supported by independent geological evidence. If uncorrelated, the residuals should be discarded as being noise. In all cases, the final analysis of misfits provides indirect control of the validity of the assumptions made.

4. Previous studies

4.1. Numerically generated polycrystals

In order to test the validity of this method, inversion was first applied to stress determination from monophase, numerically generated polycrystals (Laurent et al., 1990). The principle consists of: (1) generating random optical axes and related e planes; (2) choosing one deviatoric stress tensor T; (3) calculating the resolved shear stress for each e plane by application of T; and (4) applying the inverse method for finding T. Ideally, it is assumed that the e planes are twinned (respectively untwinned) if τ_s is greater (respectively lower) than the critical value τ_a. The results show a maximum discrepancy of about 2° from the theoretical stress orientations; for the differential stress values, the maximum departure reaches 12.5%, but average values are comparable to the theoretical ones.

It should however be noted that the study based on synthetic polycrystals does not meet the problem of heterogeneous grain size and grain size distribution that raises in natural samples. Furthermore, no heterogeneous distribution of stress at the grain scale that may occur in nature due to the nearly random grain shape distribution (e.g., indenter grains) occurs, so that the basic requirement for homogeneous stress at the grain scale is always fulfilled. The value of the departure from the theoretical stress orientations and magnitudes in numerically generated aggregates is therefore certainly much less than the expected uncertainties in natural samples (see below). As a consequence, the study on numerically generated polycrystals only provides evidence for the intrinsic validity of the inversion process: the reconstructed stress orientations are close to the theoretical ones, and the differential stress magnitudes are obtained as functions of the yield stress value for twinning adopted in computation.

4.2. Natural polycrystals

Naturally deformed carbonate samples have been studied in platform domains, in the southern Rhinegraben (Larroque and Laurent, 1988) and in the Quercy area (Tourneret and Laurent, 1990), and have led to the determination of regionally significant paleostress orientations. More recent tectonic investigations at the microscopic scale have systematically been combined with the analysis of fault slip data in order to provide independent constraints on the stress tensors determined from calcite twin data (Lacombe et al., 1990, 1992, 1993). These combined analyses, carried out in various geologic settings (Burgundy platform, Pyrenean foreland, Taiwan orogen) have demonstrated the local and regional consistency of the stress tensors derived from the inversion of calcite twin data in simple (monophase) as well as complex (polyphase) tectonics settings, and also emphasized the advantages and the limits of both methods of paleostress reconstructions.

However, in contrast to numerically generated polycrystals, natural aggregates may display heterogeneous distribution of grain size and grain shape as well as polyphase crystalline deformation, and these factors are found to greatly influence the expected confidence interval of the calculated stress orientations and magnitudes. The stress orientations obtained from calcite twin data are generally found consistent with the results of microfault analysis within a range of about 10–15°, but the differential stress magnitudes are found to display a relatively wide variability for a given tectonic event.

Considering a given stress tensor, and a limestone sample displaying a nearly homogeneous grain size and no preferred crystallographic orientation, the determination of differential stress magnitudes requires the knowledge of the critical resolved shear stress needed to activate twinning, as well as the precise definition of the percentage of twinned planes compatible with the tensor (see Section 3). The obvious difficulties that occur during the analysis of natural twin sets consist of the poor control on the results, because many parameters that influence in practice the calculation of stress magnitudes (grain size, polyphase tectonism, yield stress value) may vary simultaneously. As a consequence, most uncertainties in our determinations are due to the variability of natural phenomena at all scales, including stress perturbations in rock masses due to lithological or structural inhomogeneities (Lacombe et al., 1992).

5. Interest of the experimental approach

The determination of the Φ ratio and the differential stress magnitudes based on natural samples is thus subject to various uncertainties. In order to define these uncertainties more precisely, we conducted new experiments on deformation of calcite aggregates. The method consists of submitting samples to axial compression ($\Phi = 0$) under various temperatures, confining pressures ($\sigma_2 = \sigma_3$) and differential stresses, and to examine the resulting mechanical twin sets in the samples (Fig. 2). These twin sets are analyzed by inverse methods and interpreted in terms of stress orientations and differential stress magnitudes, which are in turn compared to the applied stress conditions. In practice, this method is somewhat similar to the analysis of numerically generated polycrystals (the applied stress conditions are known), but the examined data now consist of actual measures of true calcite grains, which do display particular shapes and sizes. This experimental approach will provide a test of the reliability of stress tensor determination based on the inversion of cal-

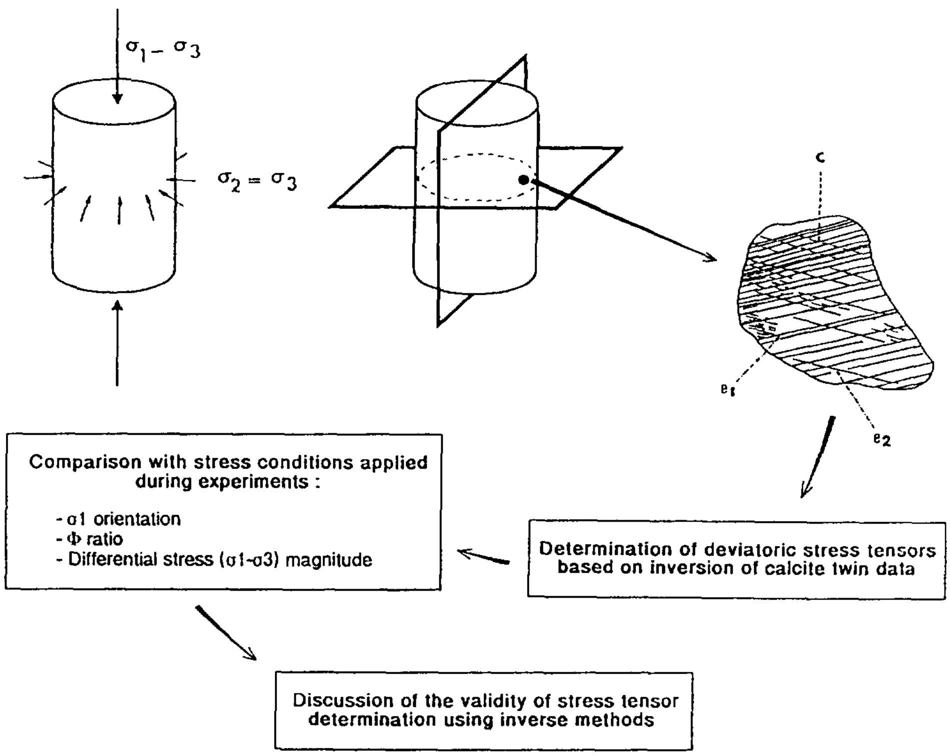

Fig. 2. Principle and aim of the inverse analysis of calcite twin data from experimentally deformed samples.

cite twin data. It will further allow a discussion of the validity of the basic assumption of a nearly constant value τ_a of the yield stress in natural samples, as well as uncertainties of the determination of differential stress magnitudes.

6. Description of experiments and results

6.1. Limestone sample: sample 1

The first sample is of a Bathonian limestone which was collected in a slightly deformed tabular platform, east of the French Massif Central (Buxy quarry). The sample displays large calcite monocrystals that correspond to subcircular crinoidic fragments with mean diameter of 300 μm. The sample additionally exhibits vertical stylolitic joints with horizontal peaks oriented N–S that probably developed during the Eocene 'Pyrenean' compression (e.g., Bergerat, 1985). In the reference sample, the main structures are due to pressure-solution. Only few straight, narrow $\{01\bar{1}2\}$ twin lamellae cross-cutting the host calcite crystals could be observed. These features clearly indicate that natural crystalline deformation remained small (probably less than 1%) and occurred at very low pressure and temperature. The geometry of these few lamellae additionally suggests that the orientation of the maximal principal stress σ_1 responsible for twinning was likely to be nearly parallel to the stylolitic peaks, but twins were not sufficiently numerous to allow computation of a stress tensor.

The sample (4 cm in diameter, 8 cm long) was cut vertically and parallel to the stylolitic joints. It was deformed (Fig. 3) using a servo-controlled loading apparatus at constant strain rate, room temperature, under a confining pressure P $(=\sigma_2=\sigma_3)$ of 60 MPa, and was submitted to a increasing differential stress $(\sigma_1-\sigma_3)$ from 0 to 166 MPa, the direction of compression being perpendicular to the stylolitic peaks. Loading was made at nearly 8×10^{-2}

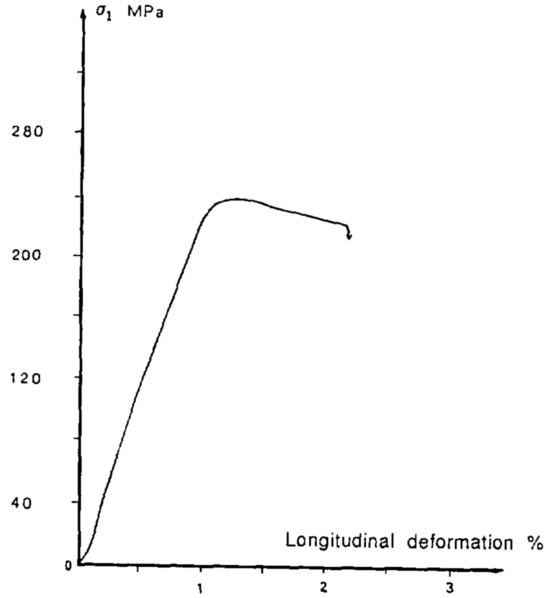

Fig. 3. Experimental stress–strain curve for sample 1. The final strain reaches 2.2%, just before macroscopic failure.

MPa s^{-1}; the final strain reaches 2.2%, just before occurrence of brittle macroscopic rupture.

6.1.1. Twin data collection and measurements

Because of the rupture of the sample, calcite twin data were collected in a single thin section cut longitudinally in the sample, with the edge parallel to the direction of compression. After experimental deformation, twin lamellae are well developed throughout the calcite grains. As in the check sample, they are very thin and generally rectilinear. Locally, gliding on $r\ \{10\bar{1}1\}$ cleavage planes is evidenced by the curvature of some e planes. Neither deformation at grain boundaries nor pressure solution processes were observed.

~ 150 calcite twin planes were measured from the thin section, by using a polarizing microscope combined with a three-axis Universal Stage. In each crystal examined, the spatial orientations of the C-axis and of the three potential e twin planes were determined, and the twinned or untwinned character of each twin plane was optically checked.

6.1.2. Results

105 twinned planes and 45 untwinned planes were measured (Fig. 4). This high percentage of untwinned planes relative to the total number of twin planes (approximately 30% of the e planes) is optimal for constraining the stress tensor solution. The inverse method leads to a tensor which accounts for 75% (78) of the twinned planes; only 1 untwinned plane (2.2%) is inconsistent with this tensor (Fig. 5). In the reference frame of the edge of the thin section, which is now assumed to be N–S, the computed tensor corresponds to a N013° axial compression ($\sigma_2 \sim \sigma_3$: Table 1). The value of the penalization function f is low (0.04).

The lowest τ_s value acting along any twinned plane accounted for by the tensor corresponds to the $\tau_{a'}$ value, i.e., 0.0512. Taking into account the value 10 MPa of the actual yield stress value, the corresponding differential stress ($\sigma_1 - \sigma_3$) calculated by

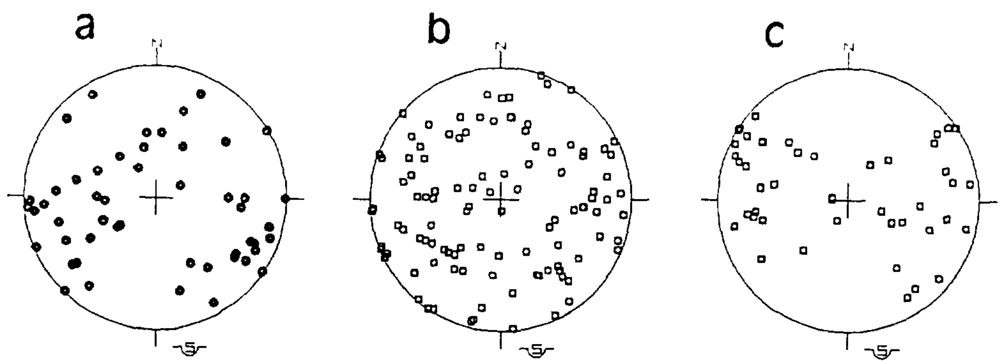

Fig. 4. Distribution of microscopic data in sample 1. Stereographic projection (lower hemisphere, equal area) of the C-axes (a), and of the poles of twinned planes (b) and untwinned planes (c) of the crystals measured in sample 1. The data are represented in the framework of the thin section, with the direction of σ_1 horizontal and close to N–S. Note the nearly random orientation of these data.

using Eq. 2 is 195 MPa, that is 17.5% higher than the expected one.

6.1.3. Discussion

The angular departure of the computed σ_1 direction (N013°) with respect to the experimental σ_1 direction (assumed to be N–S and parallel to the edge of the thin section) reaches 13°. This value is surprisingly large. However, it should be noticed that the 'primary' stylolitic peaks, which were horizontal in the core and perpendicular to the applied axial compression, are now unexpectedly oriented N103°

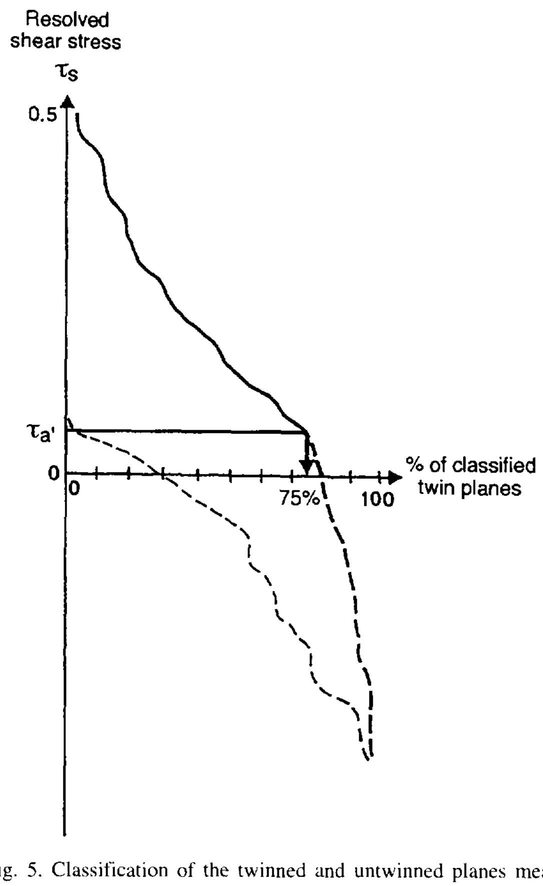

Fig. 5. Classification of the twinned and untwinned planes measured in sample 1 as a function of the (decreasing) resolved shear stress exerted on them by the tensor solution (σ_1 N013°). Heavy continuous line: twinned planes consistent with the tensor solution; heavy dashed line: twinned planes not consistent with the tensor solution; thinner continuous line: untwinned planes not consistent with the tensor solution; thinner dashed line: untwinned planes consistent with the tensor solution. The tensor solution accounts for 75% of the twinned planes; only one untwinned plane is inconsistent with it. For more details, see text.

in the thin section. They are therefore exactly perpendicular to the calculated compression (N013°). This suggests that the edge of the thin section was probably cut at 13° of the core axis and therefore of the applied compression axis, instead of parallel to both, so that in the present framework of the thin section, the direction of applied σ_1 was rather N013°. As a result, it is likely that the discrepancy of 13° between the applied and the calculated direction of compression was rather related to an error in thin section making, and we conclude that the directional discrepancy between the applied and the calculated compressions does not exceed 1 or 2°.

The low value of the Φ ratio conforms to the axial character of the experimental compression. Moreover, the magnitude of the computed differential stress ($\sigma_1 - \sigma_3$) is in good agreement with the value applied during experiments (166 MPa), which suggests that the determination of the $\tau_{a'}$ parameter, as well as the value 10 MPa for the actual yield stress value are correct (see discussion in the last section). The only untwinned plane incorporated in the solution suffered a resolved shear stress of 14.77 MPa, larger than the actual yield stress value of 10 MPa. As this untwinned plane should theoretically have been twinned, we think that it is rather due to an error in measurement concerning the untwinned character, because of the thinness of the twin lamella.

25% of the twinned planes remaining uncorrelated, the inversion process was repeated on these twinned planes as well as on the whole set of untwinned planes. The resulting tensor corresponds to a N117° compression, which is not very different from the direction of the N103°-directed stylolitic peaks. From a numerical point of view, the classification of the twin planes versus the decreasing resolved shear stress indicates that two untwinned planes receive the largest τ_s values, the twinned planes compatible with it being classified immediately after, so that the quality of this tensor is poor. However, this result (1) confirms that some twins, although not numerous, developed in response to a nearly N–S compression (in the geographical framework) before the experiments, and (2) may indicate that related twins (and very probably the stylolites of same orientation) developed at stress levels very close to the yield stress value. This point will not be discussed hereafter.

6.2. Carrara marble: samples 2, 3 and 4

The starting material used in the experiments is of Carrara marble. At the scale of the thin section, this material is quite isotropic and displays thin, rectilinear twins cross-cutting large crystals of nearly homogeneous size (200–300 μm). These twins indicate that natural crystalline deformation has occurred prior to experiments in Carrara marble, as already described by Schmid et al. (1980). Furthermore, using the inverse method reported in a previous section, Laurent (1984) determined two different stress tensors from this material, suggesting occurrence of late, low temperature twin development contemporaneous with the post-Miocene extensional tectonics in the Apennines.

Three samples of Carrara marble (1 cm long, 1 cm in diameter) were deformed. The experiments were conducted at constant strain rate (4×10^{-5} s^{-1}), at 280 and 400°C, at 40 MPa of confining pressure and various differential stresses (Fig. 6 and Table 1). In each sample, two thin sections were cut: one of them was cut perpendicular to the core axis (i.e., to the direction of applied stress), and the other one with the edge parallel to the core axis. Measurements were carried out as for sample 1. Each of these thin sections was first worked on separately; subsequently, the two sections were treated together, after restituting all the data in the framework of the thin section perpendicular to the applied axial compression, so that σ_1 axis is usually considered vertical and $\sigma_2 = \sigma_3 = P$ (Table 1).The individual results are given for the sample 2 for each thin section, but will not be detailed hereafter for the samples 3 and 4.

6.2.1. Results

Sample 2. In the thin section cut perpendicular to the direction of compression (vertical σ_1, $\sigma_2 = \sigma_3$), 135 twinned planes and only 6 untwinned planes (4% of untwinned planes) were measured. The com-

Table 1
Main characteristics of stress tensors reconstructed by means of inversion of calcite twin data for the four samples examined in this study, with respect to the stress tensors applied during experiments

	Applied tensor	Computed tensor
Limestone		
Strain: 2.2%	σ_1 N–S, horizontal	σ_1 193°–01°
$\sigma_2 = \sigma_3 = 60$ MPa	σ_2 E–W, horizontal	σ_2 283°–01°
$(\sigma_1 - \sigma_3) = 166$ MPa	σ_3 vertical	σ_3 052°–89°
	$\Phi = 0$	$\Phi = 0.135$
	$(\sigma_1 - \sigma_3) = 166$ MPa	$(\sigma_1 - \sigma_3) = 195$ MPa
Marble		
$t = 280$°C	σ_1 vertical	σ_1 063°–84°
Strain rate: 4×10^{-5} s^{-1}	σ_2 horizontal	σ_2 180°–03°
Strain: 3.2%	σ_3 horizontal	σ_3 270°–06°
$\sigma_2 = \sigma_3 = 40$ MPa	$\Phi = 0$	$\Phi = 0.100$
$(\sigma_1 - \sigma_3) = 178$ MPa	$(\sigma_1 - \sigma_3) = 178$ MPa	$(\sigma_1 - \sigma_3) = 120$ MPa
Marble		
$t = 400$°C	σ_1 vertical	σ_1 111°–82°
Strain rate: 4×10^{-5} s^{-1}	σ_2 horizontal	σ_2 013°–01°
Strain: 1.2%	σ_3 horizontal	σ_3 283°–08°
$\sigma_2 = \sigma_3 = 40$ MPa	$\Phi = 0$	$\Phi = 0.046$
$(\sigma_1 - \sigma_3) = 130$ MPa	$(\sigma_1 - \sigma_3) = 130$ MPa	$(\sigma_1 - \sigma_3) = 704$ MPa
Marble		
$t = 400$°C	σ_1 vertical	σ_1 231°–83°
Strain rate: 4×10^{-5} s^{-1}	σ_2 horizontal	σ_2 054°–07°
Strain: 3.4%	σ_3 horizontal	σ_3 324°–00°
$\sigma_2 = \sigma_3 = 40$ MPa	$\Phi = 0$	$\Phi = 0.904$
$(\sigma_1 - \sigma_3) = 178$ MPa	$(\sigma_1 - \sigma_3) = 178$ MPa	$(\sigma_1 - \sigma_3) = 185$ MPa

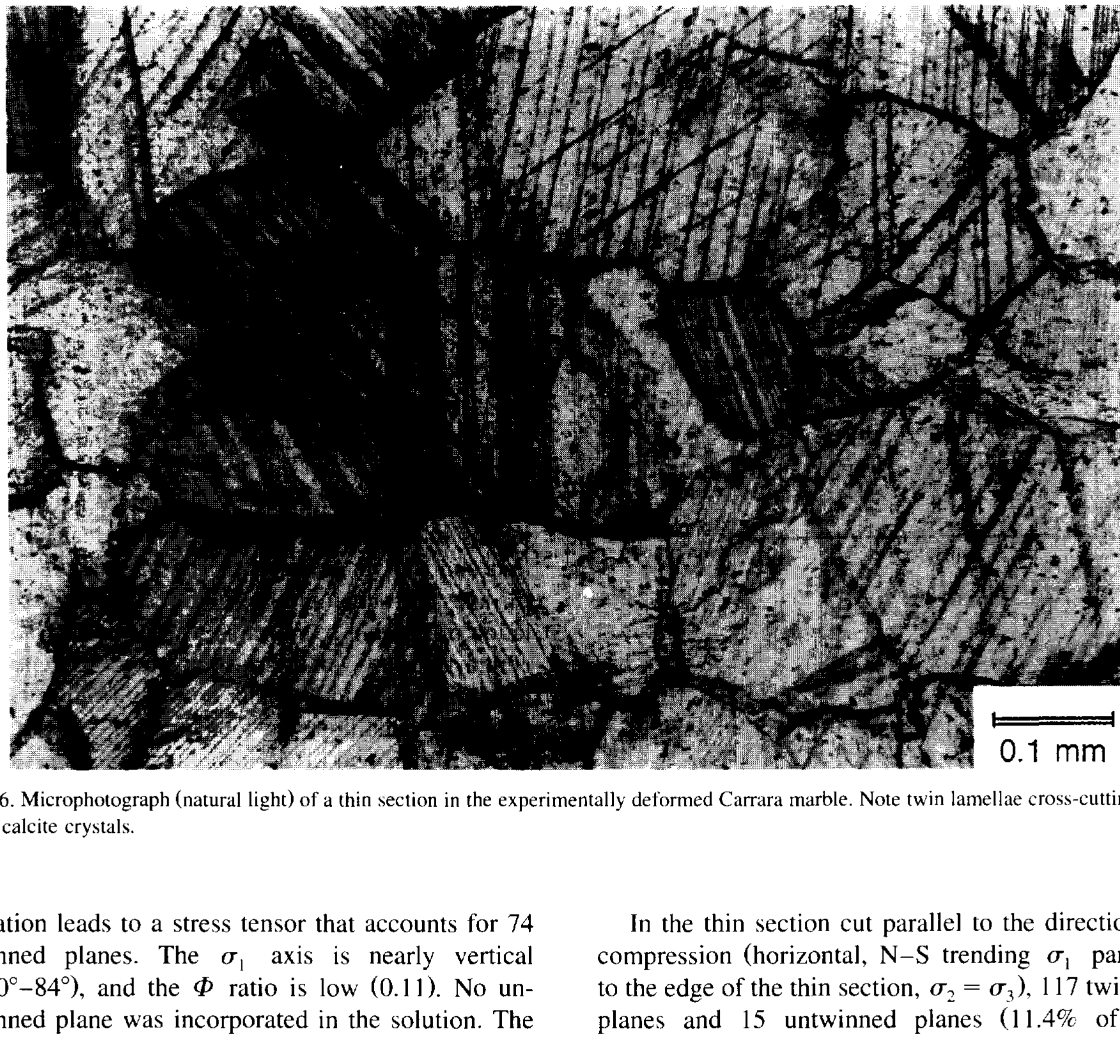

Fig. 6. Microphotograph (natural light) of a thin section in the experimentally deformed Carrara marble. Note twin lamellae cross-cutting the host calcite crystals.

putation leads to a stress tensor that accounts for 74 twinned planes. The σ_1 axis is nearly vertical (090°–84°), and the Φ ratio is low (0.11). No untwinned plane was incorporated in the solution. The τ_a' value is 0.1036.

In the thin section cut parallel to the direction of compression (horizontal, N–S trending σ_1 parallel to the edge of the thin section, $\sigma_2 = \sigma_3$), 117 twinned planes and 15 untwinned planes (11.4% of untwinned planes) were measured. The tensor solution

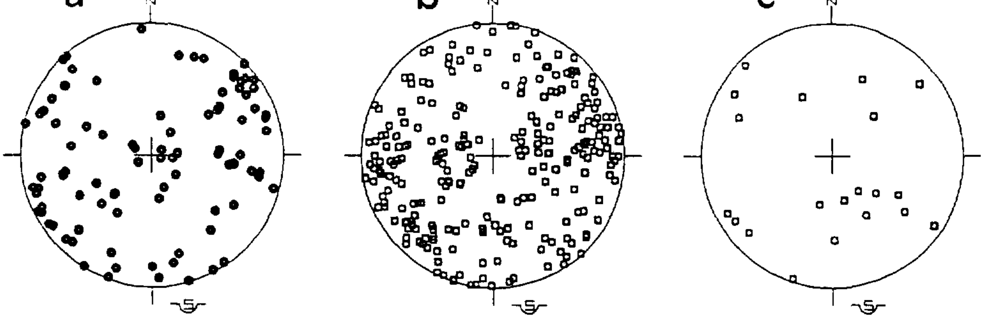

Fig. 7. Distribution of microscopic data in sample 2. Same key as in Fig. 4. All the twin data are restituted in the framework of the thin section perpendicular to the applied axial compression (σ_1 axis vertical).

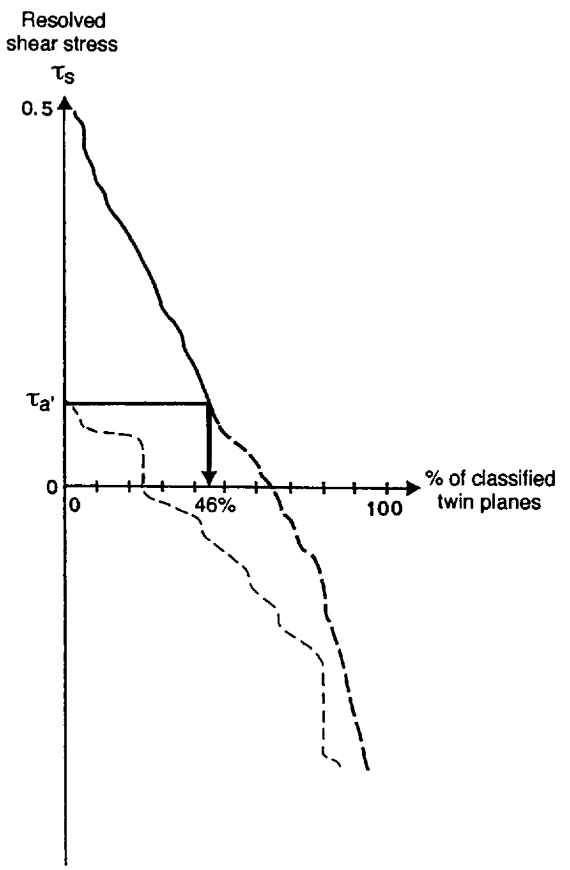

Fig. 8. Classification of the twinned and untwinned planes measured in sample 2 as a function of the (decreasing) resolved shear stress exerted on them by the tensor solution. Same key as in Fig. 5. The tensor solution accounts for 46% of the twinned planes; no untwinned plane is inconsistent with it.

accounts for 60 twinned planes and displays a subhorizontal σ_1 axis oriented 358°–02°, and a Φ ratio of 0.047. The $\tau_{a'}$ value is 0.012.

The treatment of the whole sample (both thin sections, in which 252 twinned planes and 21 untwinned planes were measured: Fig. 7) yields a tensor explaining 46% (115) of the twinned planes measured (Fig. 8). The σ_1 axis is nearly vertical (063°–84°), the Φ ratio is low (0.100) and the penalization function f equals 0 (no untwinned plane was incorporated in the solution). The $\tau_{a'}$ value is 0.0831, which corresponds to a differential stress ($\sigma_1 - \sigma_3$) of 120 MPa (Table 1). This value is slightly lower than that applied to the sample during the experiments.

It is interesting to note the difference between the results of the treatment of each individual thin section and the whole sample. The orientations of the σ_1 axes are rather similar (with respect to the orientation of the thin section), as well as the Φ ratio. In contrast, the $\tau_{a'}$ values are completely different from one thin section to the other one, and from the entire sample. In addition, the total number of correlated twinned planes (115) is lower than the sum of the twinned planes explained in each section (134). The stress tensor calculated on the whole sample (after the rotation of the two sections into the plane perpendicular to the compression) is certainly much more reliable, because of the heavier constraint on the stress tensor calculation when the whole set of untwinned planes is considered (i.e., greater number and better spatial distribution of the untwinned planes).

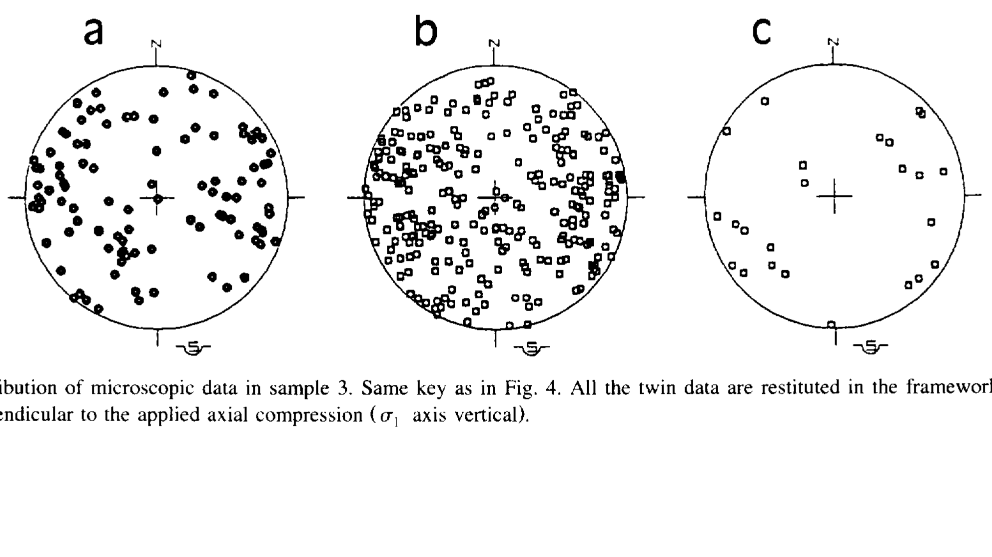

Fig. 9. Distribution of microscopic data in sample 3. Same key as in Fig. 4. All the twin data are restituted in the framework of the thin section perpendicular to the applied axial compression (σ_1 axis vertical).

Sample 3. In the two thin sections, 262 twinned planes and 24 untwinned planes were measured (Fig. 9). The computation process leads to a stress tensor that explains 60% (157) of the twinned planes measured; only two untwinned planes are incorporated in the solution. The penalization function f equals 0.06. The tensor displays a subvertical σ_1 axis (111°–82°), and a very low Φ ratio (0.046), highly consistent with the axial character of the deformation (Table 1). The $\tau_{a'}$ value is 0.0142. This value corresponds to a differential stress $(\sigma_1 - \sigma_3)$ of 704 MPa. This $(\sigma_1 - \sigma_3)$ value is unexpectedly much higher than that applied during the experiment. We therefore tried to determine the theoretical percentage of twinned planes for which, the stress axes and the Φ ratio remaining nearly unchanged, the $\tau_{a'}$ value would correspond to a differential stress $(\sigma_1 - \sigma_3)$ of 130 MPa; this value is found to be nearly 47% (that is 123 twinned planes), which indicates that the percentage of twinned planes previously retained for calculation was too large.

Sample 4. In the two thin sections, 199 twinned planes and 14 untwinned planes were measured (Fig. 10). The stress tensor solution accounts for 52% (103) of the twinned planes measured. The computed σ_1 axis is nearly vertical (231°–83°), but surprisingly the Φ ratio is very high (0.9) (Table 1). The penalization function equals 0, and no untwinned plane was incorporated in the solution. The τ'_a value is 0.0541, which corresponds to a differential stress $(\sigma_1 - \sigma_3)$ of 185 MPa, which conforms the applied value (178 MPa).

7. Discussion of results. Consequence for the calibration of uncertainties inherent in the method

7.1. Number of correlated twinned planes for each tensor solution

In the limestone sample, 75% of the twinned planes were correlated with the experimental compression, suggesting that the number of 'primary' twins that developed contemporaneously with stylolitization in response to N–S Pyrenean compression (see above) was low.

In contrast, in the samples of Carrara marbles, 40% to 54% of the twinned planes are not accounted for by the tensors solutions. These twinned planes are randomly oriented, and they remain uncorrelated when inversion is repeated, indicating that they are not consistent with a well-defined state of stress. It should be noticed that the obtained percentages of correlated twins (46% to 60%) in the samples of Carrara marbles are higher than those usually obtained in highly polyphase tectonic settings (20%–30%: Lacombe et al., 1990, 1992, 1993), but somewhat lower than those obtained in some cases from naturally deformed monophase samples (e.g., Quercy: see Tourneret and Laurent, 1990), and suggest occurrence of twinning in the starting material prior to (or during) experiments.

Several hypotheses can be proposed to account for the occurrence of such twinning. These hypotheses consist either of twins that developed in response

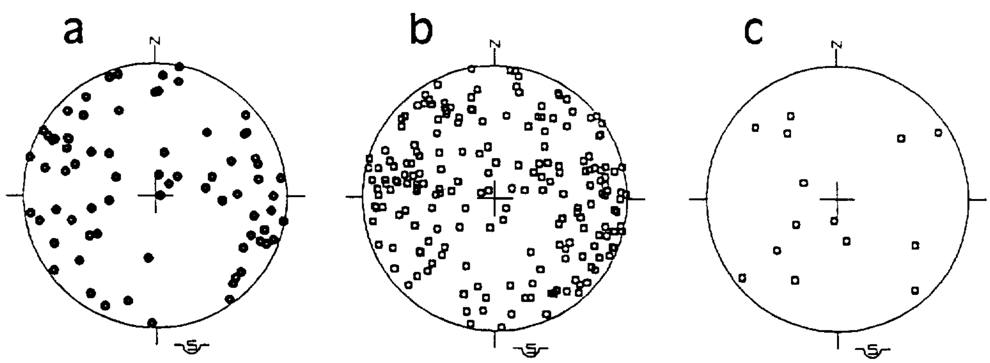

Fig. 10. Distribution of microscopic data in sample 4. Same key as in Fig. 4. All the twin data are restituted in the framework of the thin section perpendicular to the applied axial compression (σ_1 axis vertical).

to natural stresses prior to experiments (see Laurent, 1984), or of twins that developed during stress release after deformation or experimental cooling. Occurrence of twinning due to cooling effects is very probable, because the samples of Carrara marble were deformed at temperatures equal to (or higher than) 280°C. These cooling effects may be responsible for a percentage of observed twins as large as 50% (E.H. Rutter, pers. commun., 1993), which is in good agreement with the number of twinned planes defining our tensor solutions for the Carrara samples. Further experiments are needed to test the weight of cooling in generating twins, by raising temperature without loading.

7.2. Stress orientations

The inverse analysis of calcite twin data from the experimentally deformed samples demonstrates that in all cases, the computed orientation of the σ_1 axis is very similar to the direction of the compression applied during the experiments (Table 1). In addition, this orientation remains generally stable if some twinned planes are added or removed from the twin set defining the tensor solution. In the same way, the σ_2 and σ_3 axes are sub-vertical or sub-horizontal, in agreement with the experiments.

Taking into account the probable technical problem of thin section making for sample 1, our results show that the range of uncertainties of the calculated stress orientations around the theoretical ones for natural samples does not exceed $\pm 5°$.

7.3. Differential stress magnitudes

In samples 1 and 4, the computed $(\sigma_1 - \sigma_3)$ stress magnitudes are close to the differential stress value applied during experiments (deviations of 17% and 4%, respectively: Table 1). Sample 2 shows deviation of -33%; in sample 3, differential stress $(\sigma_1 - \sigma_3)$ is highly overestimated.

As for other methods of differential stress determination (e.g., Jamison and Spang, 1976; Rowe and Rutter, 1990), inverse methods may tend to overestimate differential stresses. Such a case can be illustrated by the Oligocene extension in the Burgundy and Quercy platforms, for which inversion of calcite twins clearly yields very large values of differential stress $(\sigma_1 - \sigma_3)$, which are not consistent with the thickness of the overlying sediments (Lacombe and Laurent, 1992; Burkhard, 1993). Generally, however, reasonable values are obtained (Lacombe and Laurent, 1992), and the reliability of these determinations is corroborated by independent geological indicators (such as faulting or vertical stress estimates).

As previously emphasized, during inversion, the relative percentage of untwinned planes is a very important parameter for constraining the calculation of the stress tensor, especially for determining differential stress magnitudes. If this relative percentage is very low, the numerical quality of the tensor may be poor because of the lack of constraint. In sample 3, this percentage was about 8.4%, and has led to abnormally high values of differential stress $(\sigma_1 - \sigma_3)$. When the number of untwinned planes is low, a large number of twinned planes are incorporated in the solution before the first untwinned plane to be incorporated, so that the $\tau_{a'}$ value is abnormally low, and therefore the $(\sigma_1 - \sigma_3)$ value is too high (Eq. 2). These low percentages of untwinned planes may be due to the superimposition of the experimental tensor to previous natural polyphase deformation or to cooling effects which may have resulted in twin development, thus lowering the available percentage of untwinned planes. Combination of these two effects is likely in sample 3 of Carrara marble, in which Laurent (1984) could demonstrate the polyphase character of the natural deformation at Carrara (see description of the starting material).

Except for sample 3 in which $\tau_{a'}$ determination was not sufficiently constrained because of the low number of untwinned planes, the calculation of $\tau_{a'}$ can be considered as reasonably reliable in samples 1, 2 and 4, which display a sufficient number of randomly oriented untwinned planes. $\tau_{a'}$ and the applied differential stresses being known, it is therefore easy to determine the theoretical τ_a value which should have provided $(\sigma_1 - \sigma_3)$ values very close to those applied. In sample 1, the yield stress value which would have led to the calculation of a $(\sigma_1 - \sigma_3)$ value of 166 MPa is 8.5 MPa. This value is somewhat lower than the value (10 MPa) usually adopted in calculation. The same reasoning applied to sample 2 and 4 leads to theoretical values of 14.79 and 9.63 for τ_a. It is interesting to notice that these values belong to a range of values (± 3.5) around an average value of 11 MPa, as already suggested in a previous section of this paper. Although our determinations are not sufficiently numerous to draw definite conclusions, our results show that the τ_a value of 10 MPa usually adopted in the computation process is reasonable. Further investigations are needed to confirm this preliminary conclusion.

7.4. Φ ratio

In 3 samples, the computed Φ ratio is low (0.13, 0.10, 0.04), indicating that σ_2 and σ_3 have comparable magnitudes. These results are in good agreement with the axial character of the compression ($\sigma_2 = \sigma_3 = P$, $\Phi = 0$) (Table 1). The Φ ratio in sample 4 is abnormally high. No satisfactory explanation was found. In the other samples examined in this paper, the uncertainty on the Φ value is of the order of 0.2. This range of uncertainty is similar to that estimated from comparisons with Φ ratios deduced from fault slip analysis (Lacombe et al., 1992). In the case of sample 4, however, the Φ ratio is very different from the expected one, and cannot be considered as reflecting the state of stress.

In fact, until now, there has been little control on the Φ value, even if fault slip data are available for comparison: even though they are related to the same tectonic event, twins and faults do not develop perfectly contemporaneously, so that the reconstructed Φ ratios may vary. At the present state of our knowledge, the Φ value can only be considered as a datum for which no real control is available, and therefore no discussion of uncertainty is possible; experiments in triaxial conditions will help us to better constrain the uncertainties on this parameter (work in progress).

Note that this uncertainty on the σ_2 value relative to σ_1 and σ_3 is particularly cumbersome when one addresses the problem of the determination of principal stress magnitudes for a strike-slip regime, for which σ_2 is vertical. If ($\sigma_1 - \sigma_3$) and ($\sigma_2 - \sigma_3$) are fixed, one way to determine σ_1, σ_2 and σ_3 values consists of evaluating the weight of overburden σv ($= \sigma_2$); uncertainties on σ_2 may therefore have heavy consequences on estimates of principal stress magnitudes (Lacombe and Laurent, 1992). In contrast, the uncertainty on the value of the Φ ratio has a smaller influence when σ_1 and σ_3 magnitudes are deduced by combining calcite twin analysis with rock mechanics criteria, i.e., fresh rupture and friction laws.

8. Conclusion

New experiments on deformation of calcite aggregates in axial stress conditions were performed; the preliminary results allowed to evaluate the reliability of stress tensor determination based on inversion of calcite twin data, in terms of both stress orientations and differential stress magnitudes. These experiments additionally enabled us to discuss the uncertainties of these determinations, especially in differential stress magnitudes, but did not allow an accurate quantification of these uncertainties. This study finally emphasizes the importance of untwinned planes in the inversion process: when the untwinned planes are sufficiently numerous and randomly distributed, both the Φ ratio and the differential stress magnitudes are reliably determined and actually reflect the state of stress. Further experiments carried out at low temperature and with a certain range of differential stress magnitudes (from values barely enough to initiate twinning — nearly 10 MPa — to values producing failure in the samples) will help to complement these preliminary results (work in progress).

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