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Determination of principal stress magnitudes using calcite twins and rock mechanics data

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ABSTRACT

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This paper proposes a new method for determining principal stress magnitudes, based on the use of the deviatoric stress tensor determined from computer inversion of calcite twin data. Additional evaluation of the vertical stress (weight of overburden) or of the mean stress is enough to calculate the complete stress tensor. We emphasize that the best reasoning consists of combining calcite twin analysis with rock mechanics data (failure/friction criteria), because the determination of the six parameters of the absolute stress tensor is overconstrained.

Introduction

Numerous papers have attempted to determine and completely describe the palaeostress states associated with the tectonic history of rock masses. A partial solution to this problem was found by establishing a relationship between the state of stress and the development of a conspicuous structural element in the rock itself.

Two main tools were developed and improved in order to determine the six independent parameters of the absolute stress tensor. The first one is the analysis of striated faults combined with rock mechanics data (Sassi and Carey-Gailhardis, 1987; Angelier, 1989). Based on computer inversion processes, populations of striated faults were interpreted in terms of palaeostress (Carey and Brunier, 1974; Etchecopar et al., 1981; Armijo et al., 1982; Angelier, 1984, 1989). Rock mechanics criteria (failure/friction) were additionally used in order to determine principal stress magnitudes and thus completely define the actual stress tensor (Table 1).

The second tool consists of palaeo-piezometric techniques based on crystallography, such as dynamically recrystallized grain size in quartz or twinning in calcite. It has been known since the pioneering work of Turner (1953) that analyzing twinning in calcite grains may lead to the orientation of the principal stresses responsible for the crystalline deformation. The possible use of mechanical twinning in calcite as an indicator of differential stresses has also been discussed in both a theoretical and experimental context (Friedman and Heard, 1974; Jamison and Spang, 1976; Tullis, 1980; Spiers and Rutter, 1984; Rowe and Rutter, 1990), but actual magnitudes of principal stresses have never been determined. Recently, computer-based inversion processes (Etchecopar, 1984; Laurent et al., 1981, 1990a) have supported the dynamic analysis of calcite twinning and its interpretation in terms of stress.

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TABLE 1

Compilation of previous results of estimations of principal stress magnitudes using fault slips and rock mechanics data

Reference	Rock material	Age and Orientation of palaeo stress	Palaeo stress magnitudes (MPa)
Paris et al. (1975)	Thanetian limestones (south France)	Late Eocene N–S compression	$\sigma_1 = 40–50$ $\sigma_2 = ?$ $\sigma_3 = 5$
Petit (1976)	Permo-Triassic sandstones of Morocco	Post-Cretaceous N–S compression	$\sigma_1 = 50$ $\sigma_2 = 30$ $\sigma_3 = 10$
Rispoli (1981) Rispoli and Vasseur (1983)	Jurassic limestones (south France)	Late Eocene N–S compression	$\sigma_1 = 5–20$ $\sigma_2 = ?$ $\sigma_3 = 1–2.5$
Bergerat et al. (1982) and (1985)	Jurassic limestones of Germany	Late Eocene N–S and Miocene NE–SW compressions	$\sigma_1 = 50–130$ $\sigma_2 = ?$ $\sigma_3 = 6–12$
Gaviglio (1985)	Campanian limestones (south France)	Late Eocene N–S compression	$\sigma_1 = 19–310$ $\sigma_2 = 50–69$ $\sigma_3 = -5–50$
Sassi and Carey (1987)	Quaternary formations in Greece	Quaternary ENE–WSW compression	$\sigma_i = ?$ $\sigma_1 - \sigma_3 = 6–160$
Angelier (1989)	Miocene formations of Arizona	Miocene ENE–WSW to ESE–WNW extension	$\sigma_1 = 10$ $\sigma_2 = 3$ $\sigma_3 = 0.6$
			$\sigma_1 = 25$ $\sigma_2 = 10$ $\sigma_3 = 6$

This paper presents a new method for the complete determination of principal stress magnitudes. This method primarily combines the deviatoric stress tensor determined from the inversion of calcite twin data with rock mechanics criteria.

Principle of determination of the complete stress tensor using calcite twins

The absolute stress tensor contains six independent variables. Three variables describe the orientations of the three principal stress axes; the three remaining values describe the magnitudes of the principal stresses σ_1, σ_2 and σ_3 (here σ_1 is the greatest compressive stress, σ_2 the intermediate stress and σ_3 the least compressive stress, with compressions counted as positive).

In fault tectonics, due to the fact that only fault slip orientations are used to determine the stress, one only has access to four parameters, which define the "reduced" stress tensor (Angelier, 1989). This reduced stress tensor T_r describes the orientations of the three principal stress axes and the stress ellipsoid shape ratio $\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ (i.e., there is one relationship between the magnitudes of σ_1, σ_2 and σ_3). In the Mohr diagram (tangential stress (τ) versus normal stress (σ_n)), this reduced stress tensor, T_r, is represented by a dimensionless Mohr circle. T_r is such that the complete stress tensor T is an affine function of T_r, namely:

$$T = kT_r + lI$$

where k and l are scalars ($k > 0$) and I is the unit matrix (Etchecopar et al., 1981; Angelier, 1984, 1989).

Adding any isotropic stress, lI, to T_r or multiplying T_r by a positive scalar, k, does not change the orientation and the sense of the shear stress on the fault planes (so that the inversion of fault slip data provides no access to k and l). However, it affects the actual magnitudes of σ_1, σ_2 and σ_3 and results in a shift of the Mohr circle along the normal stress axis and a change in the size of this circle (Angelier, 1989). Consequently, both the scale factor (k) and the position of the Mohr circle on σ_n axis (l) are not available to define completely the actual stress tensor. Determination of the two remaining unknowns based on reasoning in the Mohr space requires the additional use of both rupture and friction laws.

Calcite twin analysis is more appropriate for palaeostress estimation. In contrast to fault slip analysis, the computer-based inversion of calcite twin data leads directly to the calculation of the deviatoric stress tensor responsible for twinning, that is, five independent parameters among the six of the absolute stress tensor (Etchecopar, 1984; Laurent et al., 1990a). These five parameters describe palaeostress orientations as well as differential stress magnitudes ($\sigma_1 - \sigma_3$) and ($\sigma_2 - \sigma_3$) (i.e. two independent relationships between magnitudes of σ_1, σ_2 and σ_3) (Lacombe et al., 1990a). Among these five parameters, four result directly from twinning geometry and define the reduced stress tensor (as for fault slip analysis). The fifth one corresponds to the scale factor of the tensor (i.e. scalar k, defined above) and depends on the existence of a constant critical yield stress value for twinning, τ_c ($\tau_c = 10$ MPa according to the experiments of Turner et al. (1954)). It is not the aim of this paper to discuss the mathematical basis for the computer technique we use to calculate the deviatoric stress tensor, which was extensively described in Etchecopar (1984) and Tourneret and Laurent (1990).

Knowing the five independent parameters of the deviatoric stress tensor (orientations of σ_1, σ_2 and σ_3 axes and differential stress values ($\sigma_1 - \sigma_3$) and ($\sigma_2 - \sigma_3$)), a single parameter is still missing to allow us to define the complete stress tensor. This missing parameter is the isotropic component of the tensor (scalar l defined above). Calcite twins provide no access to this last unknown, because the critical resolved shear stress required to activate twin gliding is independent of normal stress (Turner et al., 1954). In order to assess the actual magnitudes of σ_1, σ_2 and σ_3 it is necessary to fix one of them; or at least to determine a third additional relationship between them (Laurent et al., 1990b).

Calcite twins, palaeo-depth estimation and principal stress magnitudes

The simplest way to determine one principal stress consists of evaluating the weight of overburden, ρgh, assuming that it corresponds to the vertical stress (σ_1, σ_2 or σ_3 according to the type of deformation). Determination of the weight of overburden requires estimation of the palaeodepth at the time of the tectonic event considered, as well as the average density of the overlying rocks. Such reasoning has previously been used in association with fault analysis (Bergerat et al., 1985; Angelier, 1989). We will discuss the palaeodepths of deformation predicted from calcite twins in another section of this paper.

In few situations, the mean stress $(\sigma_1 + \sigma_2 + \sigma_3)/3$ may also be reasonably evaluated and yields the isotropic component of the tensor.

Calcite twins, rock mechanics and principal stress magnitudes

In the absence of reliable data pertaining to the palaeodepth of deformation, the missing parameter of the absolute stress tensor can also be determined through the use of the Mohr diagram, by combining calcite twin analysis with rock mechanics. In this section, we discuss how rock mechanics criteria can be taken into account to provide additional constraints on the actual magnitudes of σ_1, σ_2 and σ_3.

In the method we propose, we basically use calcite twin data to reconstruct the absolute stress tensor. Conjugate (i.e. newly formed) faults which may be found associated with calcite twins are considered only as an indicator of fresh failure. Consequently, for each palaeostress system, the first step of our technique consists of identifying, within the heterogeneous fault population, the related subset of newly formed faults using their geometric properties (Anderson, 1942).

Basic assumptions. The following hypotheses are assumed:

(1) The deformation (strain) in the coarse-grained limestones we study is very small (less than 1%), so that deformation at grain boundaries is negligible and calcite aggregates essentially deform by twinning on [$10\bar{1}2$] planes.

(2) The stress tensor is homogeneous in space and time, especially for both a given site and a given tectonic event.

(3) Subsets of calcite twins and newly formed faults are considered to have developed contemporaneously at the scale of geologic time (i.e. during a single tectonic event) provided that they are related to the same palaeostress orientation.

(4) Palaeostress orientations and differential stress magnitudes ($\sigma_1 - \sigma_3$) and ($\sigma_2 - \sigma_3$) (i.e., the deviatoric stress tensor) can theoretically be determined from computer inversion of calcite twin data.

(5) The deviatoric stress tensor determined from calcite twins can be shown as a classical Mohr circle (shear stress/normal stress—τ/σ_n), with no experimental origin. The size of this Mohr circle (i.e., the diameter of the circle) is thus given by the differential stress values ($\sigma_1 - \sigma_3$) and ($\sigma_2 - \sigma_3$).

The technique we propose uses the common reasoning on stress in the Mohr space (Jaeger and Cook, 1969; Sassi and Carey-Gailhardis, 1987; Angelier, 1989; Rowe and Rutter, 1990). We consider the size of the Mohr circle associated to the stress system and its actual position along the normal stress axis to determine stress magnitudes.

State-of-stress determined from calcite twins and its relation to faulting. In this section, we aim at discussing how a stress system characterized by constant orientation of stress axes is likely to produce both faults and calcite twins during increasing stress magnitudes.

First, it must be noticed that, as for other techniques of palaeostress estimation based on calcite twin analysis (see for example Rowe and Rutter, 1990), the palaeo-piezometric technique we use leads us to determine, for a given palaeostress orientation, the peak differential stress ($\sigma_1 - \sigma_3$) attained during the tectonic history of the rock mass. In effect, according to the computer process we use (Etchecopar, 1984; Tourneret and Laurent, 1990), the differential stresses related to a given palaeostress system are computed by taking into account the maximum percentage of twinned planes consistent with it in terms of resolved shear stress.

Let us consider a stress system with constant orientation of stress axes. During increasing stress in the rock mass, calcite twinning occurs until brittle deformation (especially slips on fault surfaces) releases stress. Due to the low value of the critical resolved shear stress for twinning in calcite (about 10 MPa), twin development generally requires a lower differential stress compared to brittle rupture or to sliding on previously formed faults. Therefore, during increasing stress, most of calcite twins presumably develop first. Based on rock mechanics, it is known that the brittle deformation which will probably occur first is sliding along well-oriented pre-existing planes, because the stress level needed for frictional sliding on such surfaces is less than that required for developing new faults.

If stress still continues to increase, twin gliding is activated on crystallographic planes for which the resolved shear stress was previously too low, until fresh faulting (i.e. newly formed faults) develop. The development of these newly formed faults is thus associated with the maximum stress level sustained in the rock mass. This suggests that, if both reactivated and newly formed fault planes are related to a given palaeostress system, the reactivation of inherited well-oriented discontinuities did not release sufficient stress to prevent fresh rock failure. Recalling that our palaeo-piezometric technique provides the maximum differential stress attained during a given tectonic event, the value ($\sigma_1 - \sigma_3$) we obtain should be representative of the stress which induced rock failure (rather than frictional sliding).

Constraint from failure envelope. For a given tectonic event and a given site, our method thus consists of finding the values of σ_1, σ_2 and σ_3

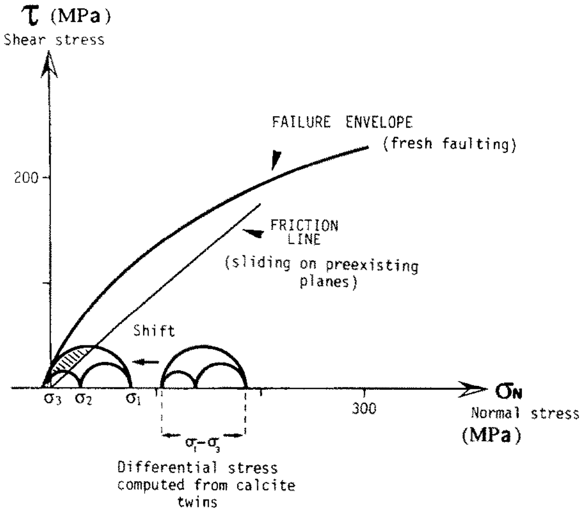

Fig. 1. Mohr diagram to illustrate conditions required for compatibility between newly formed faulting, sliding on preexisting planes and calcite twinning during a given tectonic event. The size of the (σ_3,σ_1) Mohr circle is given by differential stress values estimated from calcite twins. For a given palaeostress system, the search for compatibility between occurrence of faulting and twinning implies that: (1) the (σ_3,σ_1) Mohr circle should be tangent to the experimental failure envelope; and (2) all points representing inherited planes along which slips are consistent with the stress system, should lie in the shaded area, above the friction line. These rock mechanics criteria may be used for determining constraints on the position of the Mohr circle along the normal stress axis (i.e., the isotropic component of the tensor), and thus fixing the actual values of σ_1, σ_2 and σ_3. The intact rock failure curve and the small displacement frictional sliding line are for limestones petrographically similar to the Montalieu limestones (Riffault, 1969). For more details, see text.

required for compatibility between newly formed faulting, frictional sliding and calcite twinning. The theoretical principle of our technique is illustrated graphically in Figure 1.

Rupture in rocks occurs when the differential stress $(\sigma_1 - \sigma_3)$ is large enough to reach the failure threshold and to create newly formed (conjugate) faults. By definition, the normal and the shear stress magnitudes for conjugate faults correspond to a point on the (σ_3,σ_1) Mohr circle. Due to the fact that such faults are newly formed, the Mohr circle should be tangent to the failure envelope at the corresponding point. As a consequence, if calcite twins provide values of differential stresses, the diameter of the Mohr circle (σ_3,σ_1) is fixed, and this additional requirement for tangency between the Mohr circle and the failure envelope is sufficient to determine the magnitudes of the principal stresses completely. Therefore, if sets of newly formed faults are found associated with calcite twins, fitting the theoretical (σ_3,σ_1) Mohr circle deduced from calcite twins with the failure envelope, in order to provide stress values just before rupture, is reasonable. So, fitting the two curves constrains the position of the Mohr circle along the normal stress axis. The true values of principal stresses are thus fixed, as well as the missing isotropic component of the absolute stress tensor (scalar l defined above).

In addition, slips along inherited fractures may also be found related to the same palaeostress system (i.e., these slips are consistent in terms of reduced stress tensor). If so, and if the friction law is known (Byerlee, 1978), all points that represent these pre-existing planes should lie above the friction line in the Mohr circle (Fig. 1). Otherwise slip along these planes would not occur. This requirement obviously imposes another constraint on the position of the Mohr circle along the normal stress axis. Consequently, frictional sliding or evaluation of the palaeodepth of deformation may be used in addition to the failure criterion discussed above in order to determine the six parameters of the complete stress tensor. In this case, the determination of principal stress magnitudes is overconstrained. Not only can the remaining unknowns of the actual stress tensor be accurately evaluated, but discrepancies between the independent parameters will be detected.

Application to a field example

The understanding of the natural distribution of palaeostress orientations and magnitudes requires a detailed study of a large area in which the structural geometry can be well defined and the displacements are small. We thus applied our method for estimating palaeostress magnitudes to the Burgundy platform (eastern France). In each sample of Jurassic limestone, the calcite grains had no preferred crystallographic orientation and showed a well-defined extinction between crossed polars. These grains contained very thin straight twin lamellae, indicating that deformation had been small.

From each sample, we identified and separated different twinning events (in terms of stress orientations and differential stress magnitudes) using the computer-based technique described in Etchecopar (1984) and Tourneret and Laurent (1990). We first determined the optimal percentage of twinned planes consistent with a first stress tensor. This tensor and the related subset of calcite twin data were defined according to the requirement that the computed-resolved shear stress should be larger than the critical yield stress value for twinned planes accounted for by this tensor, and, simultaneously, smaller than the critical yield stress value for the whole set of untwinned planes (i.e., the potential *e* twin planes whose spatial orientation is known and on which twin gliding was not activated). When the best solution was determined, the twinned planes consistent with it were withdrawn, and we repeated the process on the remaining data. This process allowed us:

(1) to recognize the polyphase character of the crystalline deformation;

(2) to separate different twinning events and related data subsets on the basis of consistent palaeostress orientations and magnitudes.

However, no evidence of relative chronology between the twinning episodes was found. We additionally used fault slip data (1) to provide a microstructural control on the palaeostress tensors derived from calcite twins, and (2) to establish the chronology of tectonic events. The detailed results were published in Lacombe et al. (1990a). Only the succession of palaeostress orientations is shown again here to illustrate the consistency of stress orientations reconstructed from both indicators (Fig. 2). Data suggest that successive stress regimes include:

(1) NNE–SSW extension, probably Albian–Aptian in age and which may be related to the Mesozoic evolution of the Tethys belt (Dercourt et al., 1986).

(2) N–S compression, late Eocene in age, related to the Iberia–Eurasia collision.

(3) NW–SE extension, Oligocene in age, related to the west European rifting.

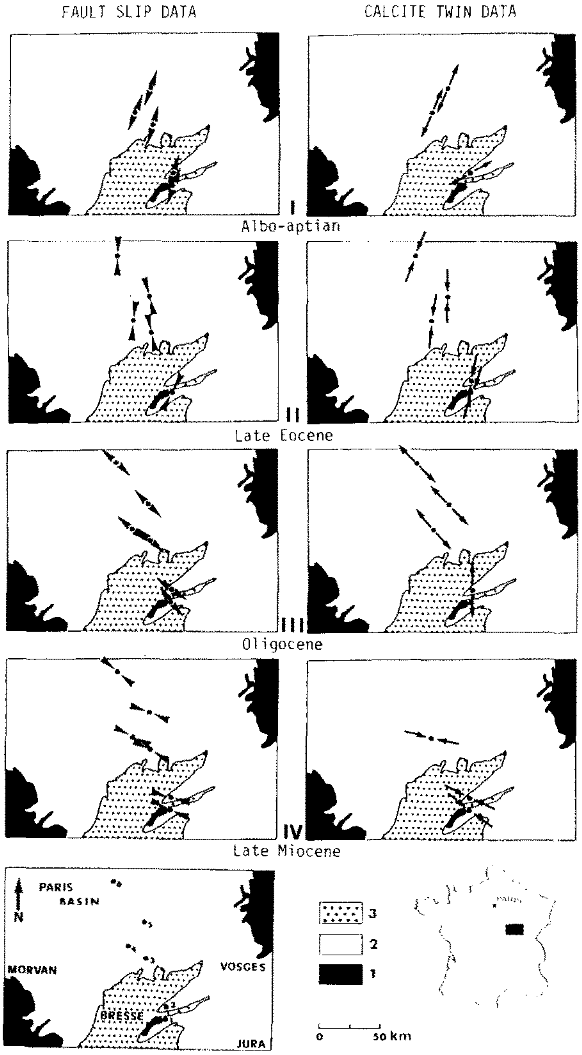

Fig. 2. Successive palaeostress orientations reconstructed from faults and calcite twins in the Burgundy platform. (I) NNE–SSW extension (probably Albo-Aptian). (II) N–S compression (late Eocene). (III) NW–SE extension (Oligocene). (IV) WNW–ESE compression (late Miocene). *1* = Hercynian basement; *2* = Mesozoic sedimentary formations; *3* = Oligocene Bresse graben; Small black arrows indicate σ_1 axis for compressional events and σ_3 axis for extensional events (after Lacombe et al., 1990b).

(4) WNW–ESE compression, Miocene–Pliocene in age, related to the Alpine collision.

Deformation was clearly polyphase in the outcrops investigated, but effects of all four events on calcite twinning were only detected at sites 2 and 4 (Fig. 2). For each tectonic event the associated differential stress magnitudes were also calculated (Lacombe et al., 1990a).

For the sake of clarity and synthesis, we have chosen to focus here on a particular outcrop (Prauthoy, site 4, Fig. 2). At this site, we detected all four calcite events, as well as newly formed and reactivated faults related to each of these events. The palaeostress orientations derived from the newly formed faults are consistent with the stress directions inferred from twin analysis (Fig. 2). For each event at the Prauthoy site, the differential stress values ($\sigma_1 - \sigma_3$) and ($\sigma_2 - \sigma_3$) were effectively computed or estimated using calcite twins (Table 2, column 1). For each episode, we also give the extreme values of differential stress determined from the other sites investigated (Table 2).

We assume that the failure envelope of the Montalieu limestone from the late Bathonian of Isère (France), determined by laboratory experiments (Riffault, 1969), can reasonably be extrapolated to the Bathonian limestone of the Prauthoy quarry, because the petrographic characteristics are nearly the same. As the differential stress magnitudes ($\sigma_1 - \sigma_3$) indicate, for each event, the size of the theoretical (σ_3,σ_1) Mohr circle associated to the tensor, the determination of principal palaeostress magnitudes is easily carried out by fitting this Mohr circle with the failure curve (as suggested in the previous section and in Fig. 1). The resulting values of principal stress magnitudes are presented in Table 2. The consistency of results with regard to frictional sliding will be developed in the next section.

Discussion of results

Order of magnitudes of stress determined from our technique

The order of magnitude of stress determined by our method is generally in good agreement with previous estimates of stress values carried out by combining fault slip analysis and rock mechanics data (Table 1). As expected, they are much lower than those estimated in the nappe tectonics setting of the Cantabrian zone of northern Spain using calcite twins (Rowe and Rutter, 1990).

The value of differential stress determined for the Oligocene episode (Table 2) is too large compared with the others. The ($\sigma_1 - \sigma_3$) value during Oligocene extension was expected to be lower than during the compressional events, as ob-

TABLE 2

Principal stress magnitudes determined by combining the deviatoric stress tensor (differential stress magnitudes) computed from calcite twins with rock mechanics data

	Differential stresses (MPa)	*	Principal stresses (MPa)	*	Predicted palaeodepth, *h* (m)
Extension	$\sigma_1 - \sigma_3 = 32$	(±1)	$\sigma_1 = 26$	(±2)	1000
(Albo-aptian?)			$\sigma_2 = 9$	(±16)	
$\sigma_1 = \sigma_v$	$\sigma_2 - \sigma_3 = 15$	(±14)	$\sigma_3 = -6$	(±2)	
Pyrenean compression	$\sigma_1 - \sigma_3 = 46$	(±12)	$\sigma_1 = 46$	(±12)	600
(Late Eocene)			$\sigma_2 = 16$	(±12)	
$\sigma_2 = \sigma_v$	$\sigma_2 - \sigma_3 = 16$	(±12)	$\sigma_3 \equiv 0$		
Extension	$\sigma_1 - \sigma_3 = 47$	(±7)	$\sigma_1 = 47$	(±7)	1800
(Oligocene)			$\sigma_2 = 25$	(±5)	
$\sigma_1 = \sigma_v$	$\sigma_2 - \sigma_3 = 25$	(±5)	$\sigma_3 \equiv 0$		
Alpine compression	$\sigma_1 - \sigma_3 = 42$	(±3)	$\sigma_1 = 42$	(±3)	approx. 0
(Miocene-Pliocene)			$\sigma_2 = 19$	(±7)	
$\sigma_3 = \sigma_v$	$\sigma_2 - \sigma_3 = 19$	(±7)	$\sigma_3 \equiv 0$		

* Extreme values of differential/principal stresses determined from all the outcrops investigated. For explanation, see text.

tained for the NNE–SSW extension. Such discrepancy was obtained previously using calcite twins, when applied to Oligocene extension in the Rhine graben (Larroque, 1987) and in the Quercy Plateau (Tourneret, 1990). It may be due either to technical process (too large number of twins consistent with this event) or to superimposition of extensional stress tensors (Tourneret and Laurent, 1990). We still do not have a satisfactory explanation for the discrepancy in the results obtained for the Oligocene extension (large value of differential stress) with respect to the other tectonic events. More detailed work is needed to determine the actual conditions of deformation during this particular tectonic phase accurately.

Consistency of predicted palaeodepths with geological data

Assuming that one of the principal stress axes is vertical during a tectonic event, and that the weight of overburden corresponds to the vertical stress, the method we propose enables one to predict the value (in dry conditions) of the weight of overburden ρgh (ρ = average density of rocks; $g = 10$ ms^{-2}; h = depth of overburden), and thus the expected value of h (Table 2).

For the two extensional episodes (Albo–Aptian NNE–SSW extension; and Oligocene NW–SE extension), calcite twin analysis indicates predominantly "normal faulting", with the σ_1 axis vertical. If we assume an average rock density of 2.6–2.7, the values of h are 1000 m and 1800 m, respectively. For the late Eocene "Pyrenean" compression, the σ_2 axis was vertical, and the corresponding value of h is 600 m. Finally, for the late Miocene "Alpine" compression, calcite twin analysis provides a vertical σ_3 axis, and the value of h was about 0 m.

In the centre of the Paris Basin, N–S extension, probably Albian–Aptian in age has been documented by seismic data (CFP TOTAL, unpublished data). At that time, the covering thickness above the Bathonian formations was about 1000 m. These data are in good agreement with the palaeodepth value (= 1000 m) that we have obtained for the NNE–SSW extension. Moreover, the other values of h (600 m and 0 m) indicate that the thickness of terranes above the formation we measured decreased with time. This is consistent with the erosional exhumation which can be expected for the Bathonian limestones of the southeastern border of the Paris Basin (Burgundy gate), which underwent uplift and emergence at the end of the Cretaceous (Rat, 1987).

In the Sancerre-Couy drill hole (GPF Program), located southwest of the Prauthoy quarry and just north of the French Massif Central, the evaluation of both present porosity and compaction rates has allowed inference of the initial porosity, which suggests that the maximum covering above the Bathonian terranes was about 450 m (Beaudoin et al., 1988). Taking into account uncertainties in this determination, the value of 450 m is of the same order as the values we have obtained independently from calcite twins. As a consequence, our results can be considered as geologically significant.

Mechanical compatibility of slips on inherited planes with regard to the complete stress tensor

If both newly formed and inherited faults are present, another way to check for the consistency of the results we have obtained consists of examining slips on reactivated fault planes (Fig. 1). These slips should be in agreement with the principal stress values deduced previously. As an example, the straight lines that correspond to the maximum friction law of Byerlee (1978):

$$\tau = 0.8 \times \sigma_n \quad (\text{for } 0 < \sigma_n < 200 \text{ MPa})$$

and to the initial friction for sliding on inherited fault planes have been drawn on the Mohr diagram corresponding to the N–S Pyrenean compression (Fig. 3). The position of this Mohr circle along the normal stress axis is fixed according to stress values determined in Table 2 for the Pyrenean compression ($\sigma_3 = 0$ MPa, $\sigma_1 = 46$ MPa). The inherited fault planes are mainly located above friction curves, indicating that slips on these pre-existing planes are consistent with the absolute stress tensor determined. Only two planes are located below the initial friction line. These planes are at large angles to the σ_1 axis, and are

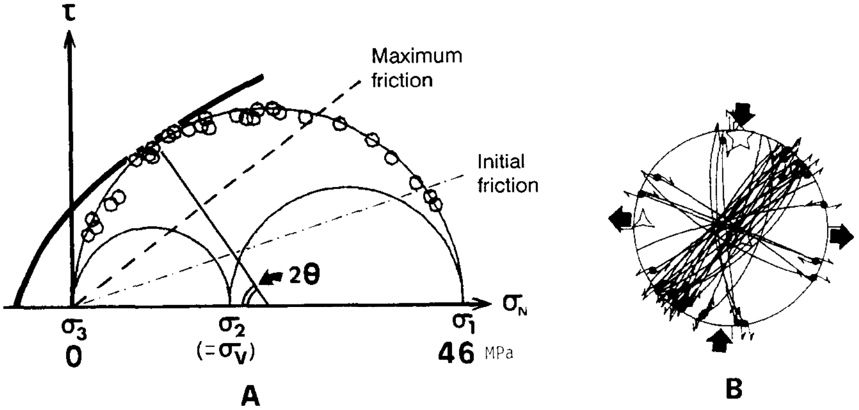

Fig. 3. (A) Mohr diagram corresponding to the late Eocene Pyrenean compression. The ($\sigma_1 - \sigma_3$) value (46 MPa) was obtained from calcite twins (Table 2). Each dot represents a measured fault plane. The failure curve is shown as a thick line, the friction curves as dashed lines. The fit of the theoretical Mohr circle (σ_3,σ_1) with the failure envelope, which fixes the principal stress values, should be in agreement with the dihedral angle, 2θ, characteristic of conjugate faults. The solution may also be checked by fitting the Mohr circle with the friction line; inherited faults consistent with the tensor should be located above this line. The value of the angle 2θ determined here for the newly formed strike-slip faults is about 55°.

(B) Fault slip data (30) corresponding to the Pyrenean compression: Lower-hemisphere equal-area projection. Thin curves = faults; dots = slickenside lineations (arrows indicate left- or right-lateral); stars = palaeostress axes, 5-pointed star = maximum compressive stress, σ_1, 4-pointed star = middle stress, σ_2; 3-pointed star = minimal stress, σ_3; directions of extension or compression shown as large black arrows.

characterized by a low shear stress (low ratio τ/σ_n). As a consequence, a speculative explanation which may account for the slips on these planes during the Pyrenean compression involves local high fluid pressure.

Limitations of the method

Computation of the deviatoric stress tensor

Application of inverse methods to calcite twin data requires several conditions to be satisfied. For instance, the sample should be weakly deformed and the optical axes and the twin planes of the crystals should be randomly distributed. Moreover, a limitation inherent to the inversion process itself relates to the relative abundance of untwinned planes with regard to the whole set of twinned planes measured. This percentage of untwinned planes provides heavy constraints on the computation of the stress tensor (see above). For polyphase samples, the ideal case involves about 25–30% of untwinned planes. In the case of natural highly polyphase deformation, the number of untwinned planes in a given sample obviously decreases, so that stress determinations (stress orientations and differential stress magnitudes) are less constrained than in the ideal case.

The calculation of differential stress magnitudes using computer inversion of calcite twin data relies on the existence of a constant yield stress value for twinning. Recent experiments on calcite deformation (Rowe and Rutter, 1990) have shown that, although it is independent of temperature and fluid pressure, the yield stress value (τ_c) is grain size dependent. A yield stress value of about 10 MPa has been adopted in this paper, because the size of the crystals that we have examined was homogeneous and comparable with the one of experimental samples of Turner et al. (1954). Uncertainties on the actual value, that we cannot quantify at the present time, may slightly modify the final results. However, for a given sample, this parameter does not influence the relative magnitudes of principal palaeostresses between the different tectonic phases.

Determination of principal stress magnitudes

Knowing the deviatoric stress tensor, the main limitation of the method we propose is related to the absence of sufficiently numerous fault slip data (newly formed and inherited), as in cores from drill holes and in weakly deformed areas. If this is true, only palaeodepth estimation may be used to constrain the actual magnitudes of σ_1, σ_2 and σ_3, and no additional independent information is available to check for consistency.

Conclusion

Compared with the methods of stress determination based primarily on fault slip data, calcite twin analysis provides better constraints on the determination of the complete stress tensor, because five parameters are directly available. In addition to the reduced stress tensor, access to the scale factor of the tensor is possible, based on the existence of a constant yield stress value for twinning. Determination of the absolute stress tensor requires only one additional piece of information: palaeodepth of deformation or failure criterion (if fresh faulting is observed). Combining calcite twin data, fault slip data and rock mechanics, provides at the present time the most reliable and efficient way of completely determining the absolute stress tensor.

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