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Calcite Twins as a Key to Paleostresses in Sedimentary Basins: Preliminary Results from Drill Cores of the Paris Basin

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ABSTRACT

Paleostress reconstructions based on inversion of calcite twin data were carried out in Jurassic oolitic limestones from drill cores of the Paris basin (Château-Thierry area). The computed paleostress orientations are found to be similar to those reconstructed using fault slip data collected in outcrops of neighbouring areas. Furthermore, they are correlable with the main stages of the late Mesozoic-Cenozoic tectonic evolution of the West European platform. In addition, calcite twin analysis combined with paleodepth estimates allows determination of magnitudes of paleostresses that prevailed at depth in the Paris basin during Cenozoic times.

Since the pioneering work of Turner (1953), it is known that analysing twinning in calcite grains may lead to the orientation of the principal stresses responsible for the observed crystalline deformation. The possible use of mechanical twinning in calcite as an indicator of 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, computer-based inversion processes (Etchecopar, 1984; Laurent et al., 1981, 1990) have supported the dynamic analysis of calcite twinning and its interpretation in terms of stress. The analysis of calcite twins in carbonate samples from the West European platform and the Pyrenean foreland, carried out along with a detailed study of striated faults (Lacombe et al., 1990, 1992) have demonstrated the validity and the local and regional consistency of the stress tensors derived from the inversion of calcite twin data in polyphase tectonics setting, and emphasized the broad interest of paleostress reconstructions at the microscopic scale (Lacombe et al., 1993a).

In this paper, we analyse mechanical twin sets in calcite in drill cores from the Paris basin (Fig.1), in order to check the possibility for determining paleostress tensors from limited rock volumes collected at depth. Further, this preliminary study aims at demonstrating that calcite twin analysis may provide a new significant and very useful tool for reconstructing the tectonic evolution of sedimentary basins, especially where minor striated faults are not sufficiently numerous to allow computation of paleostresses.

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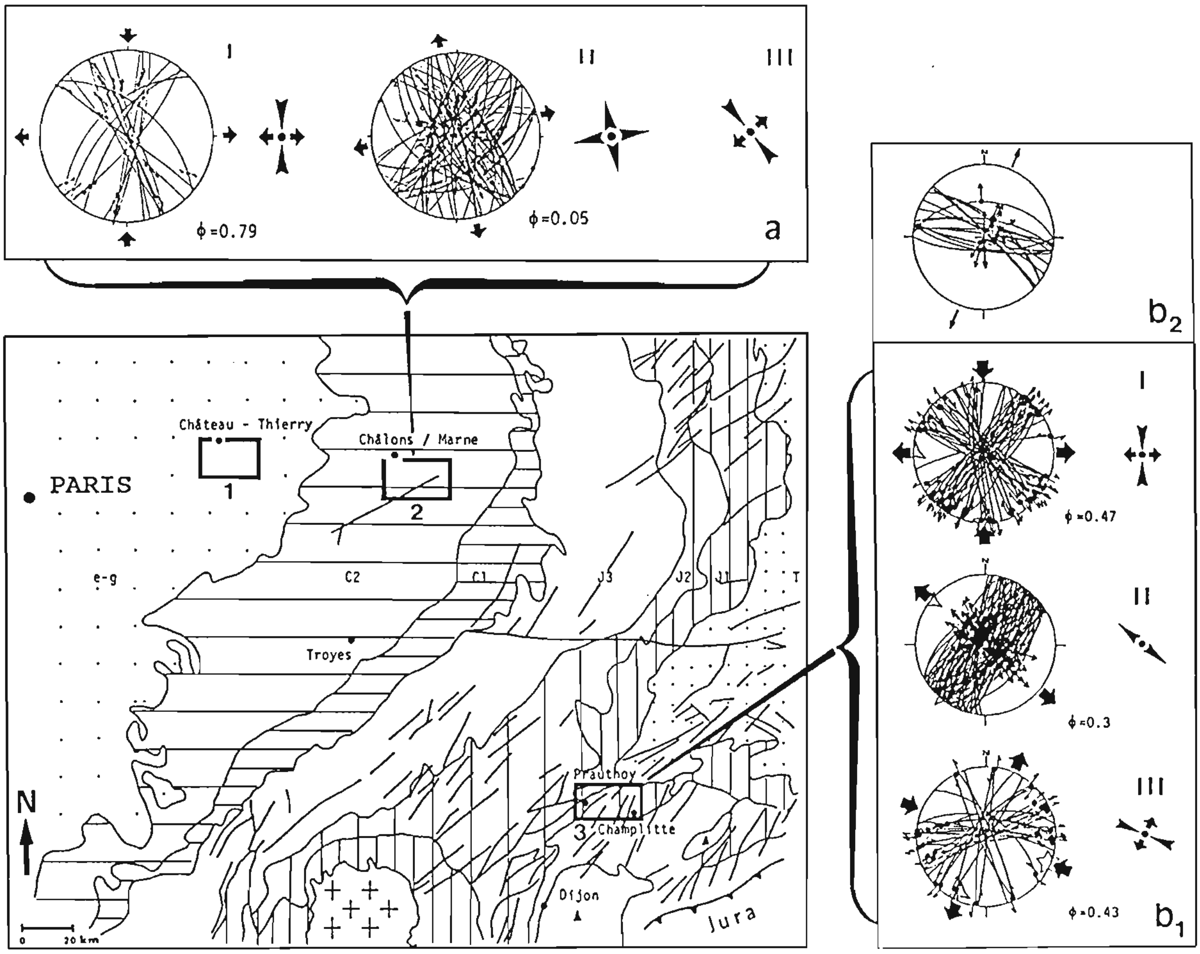

FIG. 1. Structural framework of the Château-Thierry area (Paris basin). Sedimentary formations of the Paris basin : e-g : Eocene-Oligocene; C2 : Late Cretaceous; C1 : early Cretaceous; J3 : Late Jurassic; J2 : Middle Jurassic; J1 : early Jurassic; T : Trias. Cross pattern : crystalline basement of the Massif Central. Triangle pattern : Oligocene formations of the Bresse graben. The frame 1 indicates the general location of the drill holes. The frames 2 and 3 show the areas where microtectonic data are available. (a) : data from Coulon and Frizon de Lamotte, 1988; (b1 and b2) : data from Lacombe et al., 1990. I : Eocene "pyrenean" compression; II : Oligocene extension; III : Mio-Pliocene "alpine" compression. Φ ratio, defined in text. Arrows on diagrams (lower hemisphere, equal area stereographic projection) indicate the corresponding directions of compression (convergent arrows) and extension (divergent arrows).

1 GEOMETRY OF CALCITE TWINNING

Twin lamellae are a common microscopic feature in calcite of any type and origin (Handin and Griggs, 1951; Friedman, 1964). A twin lamella results from the simple shear of part of the host crystal in a particular sense and direction along specific crystallographically defined planes (Turner et al., 1954). The resulting twinned portion of the crystal bears a mirrored crystallographic orientation to the untwinned portion across the twin plane (Fig.2). At low pressure and temperature, calcite aggregates deform primarily by twinning on *e* [01$\bar{1}$2] planes.

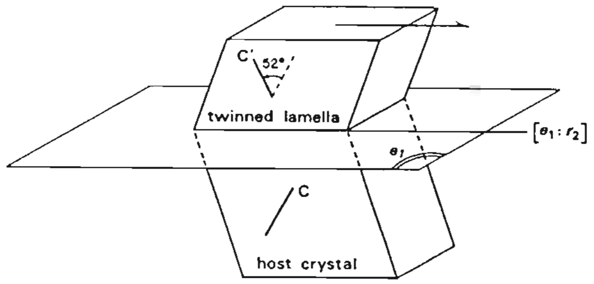

FIG. 2. Schematic sketch of a twin lamella (01$\bar{1}$2) in a calcite crystal. The e twin plane is horizontal and perpendicular to the plane of drawing. C and C' are the optic axes of the host grain and the twinned lamella, respectively. The twinning direction [e1:r2] corresponds to the direction of motion of the part of the crystal located above the twin plane. The imposed sense of shear is indicated by the arrow. A low pressure and temperature, the twin lamella is very thin and cannot be confused with the host crystal (see Fig.3).

In thin section, the resulting *e* twin lamellae are straight and very thin (about a fraction of micron : Fig.3). Each crystal contains three potential *e* twin planes that are arranged symmetrically around the C axis.

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 does not depend on temperature and confining and fluid pressures (Turner et al., 1954; Friedman and Heard, 1974), but does depend on grain size (Rowe and Rutter, 1990). Here, we adopted a value of τ_a = 10 MPa for samples displaying a nearly homogeneous grain size of 300-500 µm. These characteristics indicate that calcite twinning occurs at low differential stresses and independent of temperature and confining pressure, so that its analysis is suitable for reconstructing paleostresses in very weakly deformed carbonate cover rocks.

Each carbonate sample being carefully oriented in the field, about 150-200 calcite twin data are collected within three mutually perpendicular thin sections using a polarizing microscope combined with a 3-axis U-stage. In each crystal examined, the spatial orientations of the C axis and of the three potential *e* twin planes are thus defined, and the twinned or untwinned character of each twin plane is optically checked.

2 DATA INVERSION AND PALEOSTRESS DETERMINATION

The method which is used herein to determine principal stress orientations and differential stress magnitudes (Etchecopar, 1984) is supported by a computer-based inversion process.

2.1 Basic assumptions

Assuming homogeneous stress distribution 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:

. $\tau_s \geq \tau_a$ for all the twinned planes (or in practice, for the twinned planes compatible with this tensor, if the twin data set is polyphase);

. $\tau_s < \tau_a$ for all the untwinned planes.

2.2 Principle of inversion

The stress tensor solution is searched as a reduced stress tensor such as (σ1-σ3) is scaled to 1 [(σ1-σ3)* = 1]. The resolved shear stress τ_s acting along any twin plane therefore varies between -0.5 and 0.5.

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 (Fig.4). This classification is a useful quality estimator which allows to precisely determine the percentage of twinned planes consistent with the tensor solution.

2.3 Optimization

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 :

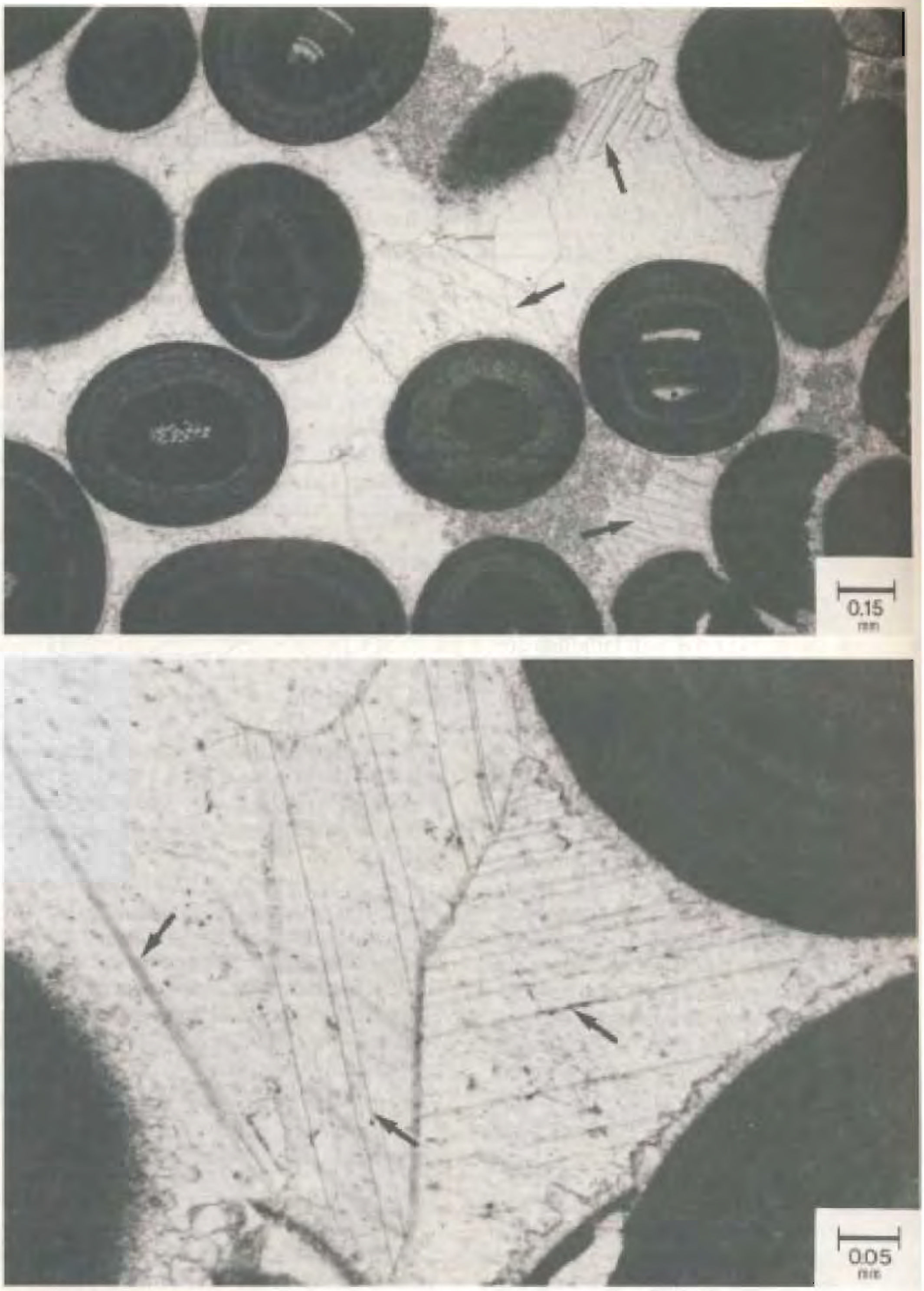

FIG. 3. Microphotographs (natural light) of thin sections in the Bathonian-Callovian limestone of the Château-Thierry area. Note the large calcite crystals that constitute the sparitic cement between the oolites. Arrows indicate narrow twin lamellae cross-cutting the host crystals.

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

where τ_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). Note that the τ_a' value may be considered as the yield stress value for the form of the tensor adopted for calculation (i.e., reduced stress tensor with $(\sigma1-\sigma3)^* = 1$).

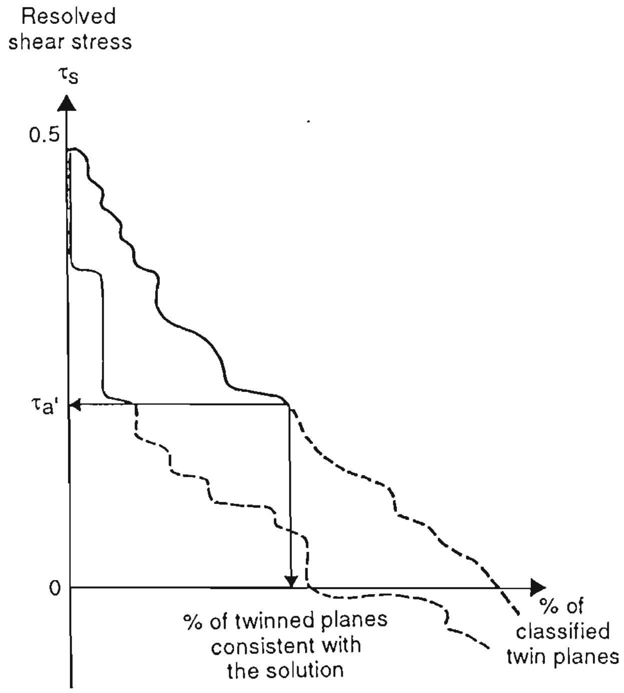

FIG. 4. Example of distribution of twinned and untwinned planes as a function of the decreasing resolved shear stress exerted on them by the tensor solution (Sample 2, WNW-ESE alpine compression). Heavy continuous line : twinned planes consistent with the tensor solution; heavy dashed line : twinned planes not consistent with the tensor solution; slight continuous line : untwinned planes not consistent with the tensor solution; slight dashed line : untwinned planes consistent with the tensor solution. The tensor solution accounts for 38% (21) of the twinned planes retained for calculation; only 1 untwinned plane is unconsistent with it. For more details, see text.

2.4 Results

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 three principal stresses $\sigma1$, $\sigma2$ and $\sigma3$ ($\sigma1 \geq \sigma2 \geq \sigma3$, compression positive) are calculated, as well as of the Φ ratio [$\Phi = (\sigma2-\sigma3)/(\sigma1-\sigma3)$, $0 \leq \Phi \leq 1$] which indicates the magnitude of $\sigma2$ relative to $\sigma1$ and $\sigma3$. Finally, the actual magnitude of $(\sigma1-\sigma3)$ is easily determined by the equation :

$$\frac{(\sigma1-\sigma3)}{(\sigma1-\sigma3)^*} = \frac{\tau_a}{\tau_a'} \qquad (2)$$

so that : $$(\sigma1-\sigma3) = \frac{\tau_a}{\tau_a'},$$

with τ_a the actual yield stress value for calcite twinning that equals 10 MPa.

2.5 Procedure for polyphase twin data sets

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. 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.

An example of the procedure when the twin data set is polyphase is illustrated in Figs. 5D to 5F (sample 2). The tensors determined account respectively for 40%, 19% and 24% of all the twinned planes measured (see also Table 1). These tensors correspond to various stress regimes, which may be related to different tectonic events (Fig. 5), but it should be noticed that the decreasing order of importance of these events as recorded by the percentage of consistent twinned planes does not necessarily reflect their succession through time.

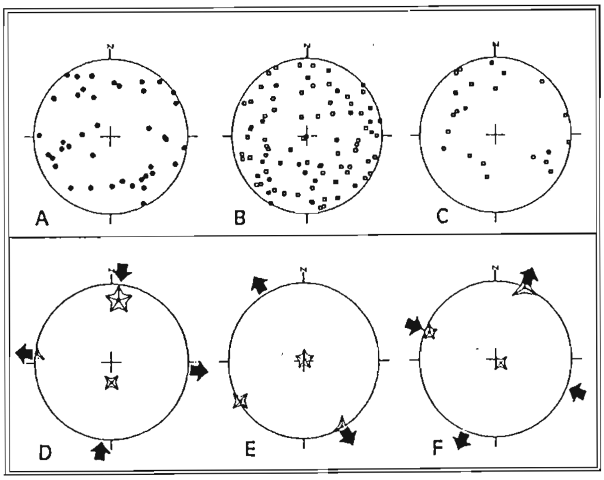

FIG. 5. Example of distribution of microscopic data in the sample 2 and characteristics of the related paleostress tensors .
A-B-C : Stereographic projection (lower hemisphere, equal area) of the optic axes (A), and of the poles of twinned planes (B) and untwinned planes (C) of the crystals measured in the sample 2 after restitution of the data into the geographical coordinate frame. Note the nearly random orientation of these data.
D-E-F : Paleostress tensors computed from inversion of calcite twin data in sample 2. Diagrams (lower hemisphere, equal area) showing the axes of the stress tensor as ornate stars with 5 ($\sigma 1$), 4 ($\sigma 2$) and 3 branches ($\sigma 3$). Corresponding directions of compression and extension indicated by black arrows.

3 APPLICATION TO PALEOSTRESS RECONSTRUCTIONS IN CORES FROM DRILL HOLES : THE PARIS BASIN AS AN EXAMPLE

In the upper part of the crust, the porous carbonate cover rocks constitute one of the main types of potential hydrocarbon reservoirs. The best exploitation of these hydrocarbons requires some important parameters to be known, including porosity and deformation of the rock material, from the crystal scale to the basin scale. More particularly, the amount and the geometry of deformation, the way these parameters evolve with increasing depth, and the possibility for their extrapolation away from drill holes within the basin, must be carefully evaluated. To this respect, the analysis of calcite twins is an useful tool - although indirect- to define precisely the mechanical behavior of the material and to describe the stress-strain relationships at depth. One of the most striking advantage of this technique is to allow determination of stress tensors from samples of only few cm^3. Calcite twin analysis thus provides a powerful additional tool for the tectonic analysis of cores from drill holes where the density of observable fractures is generally poor and often not sufficient to permit computation of paleostress tensors.

3.1 Sampling

A preliminary study of calcite twin data sets was carried out in oriented cores from petroleum drill holes from the Paris Basin (Château-Thierry area, see Fig.1), in order to check the geological significance of paleostress tensors determined at depth from limited rock volumes (Lacombe et al., 1991). Two of the three studied samples (1 and 2) come from the same drill hole (at less than 3 m one from the other, so that they can be considered as mutual check samples), whereas the sample 3 was collected in another nearby drill hole. All of them were collected at about 1,800m depth (see Table 1) in late Bathonian to early Callovian oolitic limestones (Fig.3). In thin section, the sparitic cement of these limestones display large xenomorphic calcite crystals (Fig.3) with nearly random orientations (Figs. 5A to 5C). Intracrystalline deformation consists of microtwins and straight, narrow *e* twin lamellae (Fig.3). This appearance of calcite twin lamellae, which changes as a function of deformation temperature (e.g., Laurent, 1984; Ferril, 1989), unambiguously indicates occurrence of crystalline deformation at very low temperature, when no intracrystalline slip system competes. No evidence of deformation at grain boundaries was detected, indicating that the total strain within these coarse-grained limestones remained small (less than 1 or 2%), so that these twin lamellae can reasonably be interpreted in terms of stress.

3.2 Reconstruction of paleostress orientations and relative stress magnitudes (Φ ratio)

The main result of our analysis concerns the polyphase character of the crystalline deformation. In each sample, the whole set of twin data was found unconsistent with a single paleostress tensor, indicating that twin development resulted from two or more superimposed stress tensors, each of them accounting for part of the data (see Fig.5). Several paleostress regimes could thus be reconstructed. The results are presented in Fig. 6 and Table1.

(a) *N-S to N030° compression* : A well-defined strike-slip stress regime (σ2 vertical) has been identified in the three samples, from respectively 39% of the twinned planes in the samples 1 and 2, and 18% of the twinned planes in the sample 3. The direction of maximum stress σ1 ranges from N007° to N034° (Fig. 6).

(b) *NW-SE extension* : In samples 2 and 3, evidence for an extensional regime (σ1 vertical) associated with minimum stress σ3 oriented nearly N140° have been detected (Fig.6). This event was defined in the samples from only 19% and 10% of the twinned planes, respectively. No evidence for such a twinning event was detected in sample 1.

(c) *WNW-ESE compression* : A third consistent stress regime was also determined within the 3 samples. This stress regime explains respectively 24% of the twinned planes in samples 1 and 2, and 39% of the twinned planes in the sample 3. The direction of the maximum stress σ1 is remarkably homogeneous, nearly N100°-110°, with σ3 axis horizontal or vertical (Fig.6). The Φ ratios are usually high.

These three superimposed paleostresses thus account for the development of nearly 63% of the twins measured in sample 1, 82% in sample 2 and 67% in sample 3. The remaining twin data did not allow computation of other significant stress tensors, and should be rejected as being noise.

3.3 Significance of paleostress orientations

The absence of easily observable relative chronology criteria between the twin systems at the scale of the thin section (Laurent, 1984; Lacombe, 1992) does not enable us to establish the succession of the twinning events. However, the derived paleostress orientations are very similar to those that were reconstructed using fault slip data in adjacent areas [e.g., the Châlons-sur-Marne area (Coulon and Frizon de Lamotte, 1988 : Fig. 1a) and the Burgundy platform (Lacombe et al., 1990a: Fig.1b1)], where relative chronology criteria (cross-cutting relationships between faults or superimposed slickenlines on faults planes) are available. In addition, the paleostress systems reconstructed from twin data sets are correlable in terms of orientations with the main tectonic events recognized elsewhere in the West European platform (Bergerat, 1985; Letouzey, 1986), which include :

(a) a N-S to N030° "pyrenean" compression, that reflects the stresses exerted by the Pyrenean and Alpine orogens on their foreland since the late Cretaceous and mainly during the Eocene, in response to nearly N-S Africa-Eurasia convergence (Mattauer and Mercier, 1980; Letouzey and Tremolieres, 1980; De Charpal et al., 1981; Bergerat, 1985; Letouzey, 1986; Lacombe et al., 1992);

(b) an E-W to NW-SE extension, related to the opening of the West European Rift system (Rat, 1976; Bergerat, 1985), that started in the late Eocene within the southern Rhinegraben (Villemin et al., 1986; Ziegler, 1992), and was responsible for major tectonism and crustal stretching within the Saône and Rhine grabens during the Oligocene. This extension is generally oriented E-W in the vicinity of the Oligocene grabens (e.g, Bergerat, 1985; Villemin, 1986), but may also undergo significant deviations (from E-W to NW-SE) as recognized in the Rhine-Saône Transform Zone (Lacombe et al., 1990b, 1993b) or in the eastern part of the Paris basin (Coulon, 1992). The N140° σ3 orientations we have obtained in the cores are in good agreement with these stress deviations (Coulon, 1992);

(c) a WNW-ESE to NW-SE "alpine" compression, very probably contemporaneous with the Mio-Pliocene north-westward thrusting of the Jura (Caire, 1974; Bergerat, 1985).

The tensors corresponding to the WNW-ESE (N110°) alpine compression displays high values of the Φ ratios, close to 1 (see Fig.6 and Table1). In paleostress reconstructions, high Φ values generally indicate that σ1 and σ2 have comparable magnitudes, so that they can easily permute. This problem of occurrence of stress permutations in limited rock volumes during a given tectonic event has already been addressed (e.g., Tourneret, 1990; Lacombe, 1992). From a geological point of view, this may suggest that the corresponding stress regime was rather of strike-slip extensional type. However, this interpretation seems unlikely in our case, because this stress regime is related to the north-westward tectonic emplacement of the fold-and-thrust belt of Jura, and is not found to be associated with genuine subperpendicular extension. In order to explain these high Φ values obtained, we rather propose that the tensors obtained include in fact two superimposed stress tensors. One of these tensors, purely strike-slip in type, is effectively related to the alpine compression (σ1 N110°, σ3 N020°, σ2 vertical); the other tensor corresponds to a N-S to N020° extension (σ1 vertical, σ3 N020°). Both tensors have thus a common σ3 axis (subhorizontal and oriented N-S to N020°). According to this interpretation, the high Φ values do not reflect an actual strike-slip extensional stress regime, but correspond more probably to the superimposition of two stress tensors that the inverse process in unable to unambiguously discriminate with the data set presently available. The same set of twins might have been produced by a single event, with a high Φ ratio value close to 1 (σ1 close to σ2), and a σ3 axis oriented N-S to N020°.

The existence of a N-S to N020° direction of extension may consequently be suspected from our results. Such an extensional event may correspond to the nearly N-S extension, probably Albo-Aptian in age, documented from seismic data in the Paris basin (CFP TOTAL, unpublished data), and also to the minor N-S to N020° extension recognized from microtectonic data in the Burgundy platform (Lacombe et al., 1990; Lacombe and Laurent, 1992)(Fig.1b2). Although this minor NNE-SSW extension cannot be identified with certainty based on microscopic data analysis, since it was partially overprinted by the tensor corresponding to the alpine compression, it is likely that it has affected the West European platform in Mesozoic times, especially during the Cretaceous.

In summary, the inverse analysis of calcite twin data from drill holes of the Paris basin enabled us to reconstruct successive stress tensors correlable with the main stages of the Cenozoic tectonic evolution of the West European platform. In addition, some characteristics of the stress tensors obtained suggest that some twins may also have developed in response to a late Mesozoic (Cretaceous?), N-S to N020° extension. This event was recognized from independent geological evidence, and was suspected from our microscopic data but could not be identified with certainty.

3.4 Reconstruction of paleostress magnitudes

The complete description of the paleostress fields requires the knowledge of paleostress orientations and magnitudes. Although paleostress orientations and relative stress magnitudes (i.e., the Φ ratio) are easily reconstructed by means of fault slip analysis provided that (1) outcrops are available, (2) faults are sufficiently numerous and (3) they display various orientations, the access to principal stress magnitudes is usually more difficult and requires the additional use of rock mechanics criteria, such as frictional sliding on preexisting planes or newlyformed faulting (Sassi and Carey, 1987; Angelier, 1989).

The actual stress tensor contains six independent variables. Three of these variables describe the orientations of the three principal stresses, the three others describe the magnitudes of these principal stresses. The inverse analysis of calcite twin data allows direct determination of the five parameters of the deviatoric stress tensor responsible for twinning, i.e., the orientations of the three principal stresses σ1, σ2 and σ3 and the differential stress magnitudes (σ1-σ3) and (σ2-σ3) (Table1), and thus yields one parameter more than fault slip analysis (Laurent, 1984; Lacombe and Laurent, 1992). In the Mohr diagram (Fig.7), these differential stress magnitudes fix the scale of the Mohr circles associated with the tensor. This means that the single, still missing parameter is the position of these circles along the normal stress axis (i.e., the isotropic component of the tensor). Calcite twin analysis provides no access to this last unknown, because the critical resolved shear stress required to activate twin gliding is independent on normal stress. The knowledge of this missing parameter (and hence of the complete stress tensor) requires the determination of one of the principal stresses, or at least of an additional relationship between principal stress magnitudes (Lacombe and Laurent, 1992).

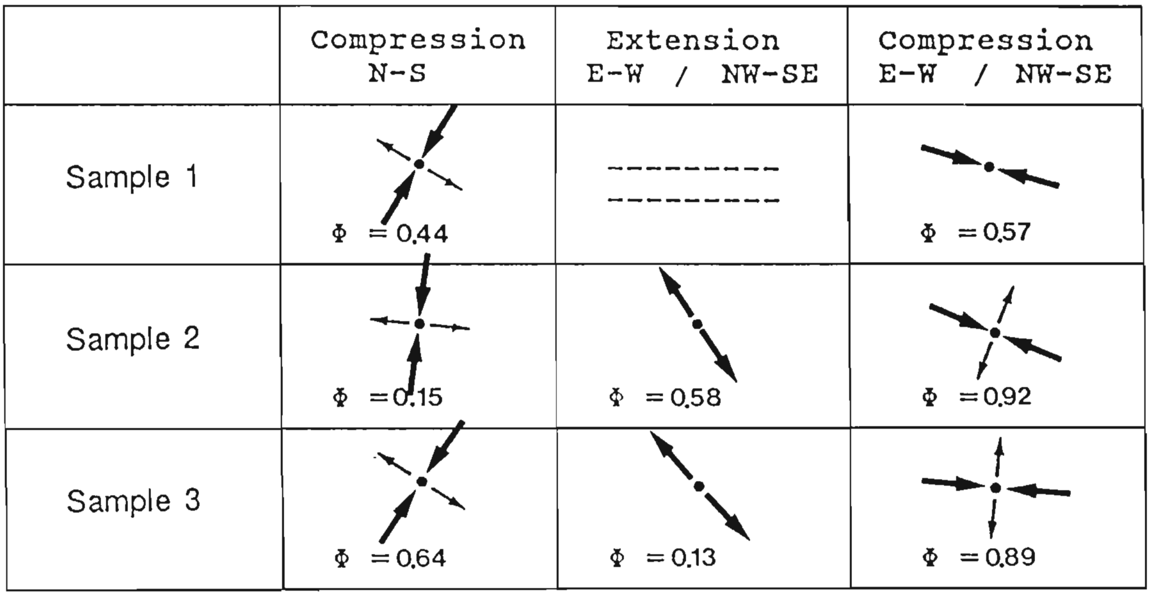

FIG. 6. Paleostress orientations and Φ ratios determined using inversion of calcite twin data in the drill cores collected in the Château-Thierry area (see Fig.1). Convergent arrows (resp. divergent arrows) indicate direction of horizontal compression (resp. horizontal extension). For numerical characteristics of the stress tensors, refer to Table 1.

TABLE 1

Main characteristics of the stress tensors determined from calcite twins in the area investigated. Trend and plunge of each stress axis, in degrees. Φ ratio, defined in text. N1, total number of twinned planes retained for calculation; N2, total number of untwinned planes retained for calculation; N3, number of twinned planes consistent with the tensor; N4, number of untwinned planes unconsistent with the tensor. τ_a' value, see text.

SITES	Lat./ Long.	$\sigma 1$	$\sigma 2$	$\sigma 3$	Φ	N1	N2	N3	N4	τ_a' Value	Differential stresses $\sigma 1$-$\sigma 3$ (MPa)	Differential stresses $\sigma 2$-$\sigma 3$ (MPa)
Château-Thierry	Sample 1 49°03'/3°26' (1815m)	031-21	275-48	136-34	0.44	166	33	66	6	0.1826	55	24
		285-14	184-38	032-48	0.57	100	33	40	5	0.1609	62	35
	Sample 2 49°03'/3°26' (1817,75m)	007-21	179-69	276-03	0.15	89	20	35	2	0.1185	84	12
		292-07	125-83	023-01	0.92	56	18	21	1	0.2068	48	44
		028-88	239-02	149-01	0.58	35	18	17	3	0.2446	41	24
	Sample 3 49°03'/3°26' (1884m)	276-28	089-62	185-03	0.89	116	40	46	5	0.0925	108	96
		214-13	317-45	111-42	0.64	70	40	21	3	0.1700	59	38
		077-88	228-01	318-01	0.13	51	38	17	4	0.1387	72	9

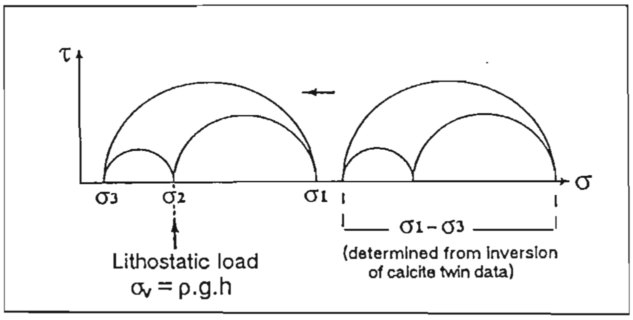

FIG. 7 : Principle of the determination of principal stress magnitudes. The size (i.e., the diameter) of the Mohr circles associated with the tensor is given by differential stress magnitudes computed by inverting calcite twin data. The position of the Mohr circles along the normal stress axis, and hence the actual stress tensor, can be determined by translating the Mohr circles until the estimated vertical stress (the lithostatic load) fits the corresponding principal stress (here, σ2, i.e., a strike-slip stress regime).

In platform domains, and at shallow depths, it is reasonable to consider that one of the three principal stresses is vertical, due to the surface free boundary. Accordingly, the estimate of the paleodepth of overburden as well as the weight of the overlying sediments at the time of the tectonic event considered is sufficient to infer the magnitude of the corresponding vertical stress σ_v (the lithostatic load). This vertical stress σ_v corresponds to σ1 for an extensional regime, σ2 for a strike-slip regime and σ3 for a compressional regime. Knowing the regional state of stress from the inversion of calcite twin data (orientations of the stress axes and Φ ratio), translating the Mohr circles (whose diameters are known) along the normal stress axis until the corresponding principal stress fits the value of the lithostatic load (Fig. 6) allows unambiguous determination of the principal stress magnitudes.

3.4.1 Determination of the vertical stress value during Cenozoic times

A synthesis of the data from the numerous drill holes within the Paris basin was carried out in order to reconstruct the subsidence history of this basin (Brunet, 1981). Among these data, those concerning the Château-Thierry area were gathered and compared, in order to provide estimates of the sediment thickness above the Bathonian-Callovian limestones during the Cenozoic times. The overburden was probably constant within a range of about 50m during Cenozoic times, and averaged 1800m.

Taking into account this 1800m paleodepth, and assuming zero pore pressure ('dry') conditions, the value of the vertical stress can be determined by:

$$\sigma_V = \rho \cdot g \cdot h, \qquad (3)$$

where h is the depth of overburden, ρ the average density of porous overlying sediments (2.1-2.2) and $g = 9.81\ ms^{-2}$. The corresponding value averages 39 MPa.

3.4.2 Determination of principal stress magnitudes at depth for Cenozoic times

For Eocene times, the vertical stress was σ2 (Fig.6), and the differential stress values are, for samples 1, 2 and 3 respectively, 55, 84 and 59 MPa for (σ1-σ3), and 24, 12 and 38 MPa for (σ2-σ3). The discrepancies between these values which were determined in samples collected close one to each other may be related either to technical uncertainties (see discussion below) or to natural variations, such as local inhomogeneities in rock masses. Preliminary results concerning the analysis of calcite twin data from experimentally deformed monophase samples (Lacombe, 1992) have shown that, as for other methods of differential stress determination (e.g., Jamison and Spang, 1976; Rowe and Rutter, 1990), inverse methods may tend to overestimate natural differential stresses. As a consequence, it seems more reasonable to retain for the Eocene tectonic event the smallest differential (σ1-σ3) stress value of 55 MPa, and therefore the corresponding (σ2-σ3) value of 24 MPa. This leads to :

$$\sigma 1 = 70\text{ MPa};\ \sigma 2 = \sigma_V = 39\text{ MPa};\ \sigma 3 = 15\text{ MPa}$$

For the Oligocene extension, the vertical stress was σ1 (normal fault regime), and the smallest differential (σ1-σ3) stress value corresponds to 41 MPa, and hence to 24 MPa for (σ2-σ3), which leads in the same conditions than previously to:

$$\sigma 1 = \sigma_V = 39\text{ MPa};\ \sigma 2 = 22\text{ MPa};\ \sigma 3 = -2\text{ MPa}$$

For Mio-Pliocene times, the determination of the vertical stress is made difficult by ambiguity discussed before, i.e., the stress tensors related to this event are either compressional (σ3 vertical : sample 1) or of strike-slip type (σ2 vertical : samples 2 and 3)(Fig. 6). In the case studied, (1) the alpine episode is usually marked in the field by strike-slip faults (σ2 vertical), (2) two of our samples (2 and 3) yielded a strike-slip stress regime, and (3) in sample 1, the σ2 and σ3 axes were not well defined (their trends and plunges are respectively : 184°-38° and 032°-48° : see Table 1). As a result, we took only into account the differential stress values obtained for the strike-slip regime (σ2 vertical). As previously for the Eocene compression, we retained the smallest (σ1-σ3) value, that is 48 MPa for (σ1-σ3) and therefore 44 MPa for (σ2-σ3). With σ2 considered as σ_v, the corresponding principal stress values are :

$\sigma 1 = 43$ MPa; $\sigma 2 = \sigma_v = 39$ MPa; $\sigma 3 = -5$ MPa

3.4.3 Discussion

Theoretically, a significant determination of differential stress magnitudes requires three conditions to be satisfied : (1) homogeneous stress tensor; (2) homogeneous grain size and grain size distribution; and (3) constant yield stress value for twinning. Especially, the uncertainties on this yield stress value, as well as some variations in grain size and in grain size distribution in our samples may account for the discrepancies between the local reconstructions. In addition, as a consequence of the computer-based inversion process, the systematic search for stress tensors solutions accounting for the maximum of twinned planes, as well as the lack of constraint on the determination of the τ_a' value when the percentage of untwinned planes is low (e.g., where tectonics is polyphase), may lead to overestimates of (σ1-σ3) values. Investigations based on experiments under uniaxial (e.g., Lacombe, 1992) and actual triaxial stress conditions will help us to better constrain the determination of stress magnitudes (work in progress).

The differential stress magnitudes being calculated from inversion of calcite twin data, the determination of principal stress magnitudes requires the additional estimate of the vertical stress σ_v (see above). The σ_v estimate is not only highly dependent on considerations about the depth of overburden, but also about actual fluid pressure. For a given paleodepth value h, adopting zero and hydrostatic pore pressure conditions respectively leads to maximum (ρgh) and minimum [$(\rho-\rho_e)gh$, ρ_e: water density] values for σ_v magnitude, and therefore for principal stress magnitudes. That means that the differential stress magnitudes and the paleodepth of overburden being fixed, principal stress magnitudes may vary within a relatively wide range of values according to the assumptions made about fluid pressure. In this paper, principal stress magnitudes were determined in 'dry' conditions, so that they must be considered as maximum values. To this respect, it is interesting to discuss the values which would have been obtained by considering hydrostatic pore pressure conditions, in order to evaluate the actual range of uncertainties between these limits. For instance, adopting hydrostatic pore pressure conditions leads to a vertical stress σ_v that averages 23 MPa, instead of 39 MPa in dry conditions; taking this σ_v value into account yields tensile stresses σ3 of -18 MPa for the Oligocene extension (instead of -2 MPa), and of -21 MPa for the alpine compression (instead of -5 MPa). Such σ3 values are clearly unconsistent with the known tensile strength of carbonate rocks, and are unlikely to have prevailed at 1800m depth. We conclude that adopting 'dry' conditions provides in our case more realistic σ3 values, which may indicate that pore pressure remained small.

Keeping in mind the various sources of uncertainties on the determination of principal stress magnitudes, it is more reasonable to retain orders of magnitudes rather than accurate stress values. The magnitudes of stresses reconstructed in the Paris basin are of the order of several tens of MPa, which is in good agreement with the intraplate stress magnitudes predicted by models (e.g., Solomon et al., 1980) or determined in forelands of fold-thrust belts (e.g., Craddock et al., 1993), but somewhat larger than those indicated by stress drops during earthquakes (Sibson, 1989). From the regional point of view, one may observe that stresses related to the "alpine" episode seem generally smaller than those related the "pyrenean" episode, although the orogenic front (the Jura mountains) is closer. This could indicate that the far-field stresses related to the "pyrenean" orogeny were transmitted far away in the platform foreland, so that they were well recorded by twinning in the sedimentary rocks of the Paris basin. We acknowledge, however, that this difference between the computed values may be not significant, considering the extent of determination uncertainties.

4 CONCLUSION

Calcite twin analysis permits reconstructions of superimposed paleostress tensors consistent with surface microtectonic data, as well as estimates of stress magnitudes related to each of the tectonic events. Calcite twin analysis thus provides a powerful tool for the tectonic analysis of cores from drill holes where the density of observable structural indicators is generally poor. The consistency of the results obtained through the analyses of both calcite twins and macroscopic tectonic features suggests that the local paleostress reconstructions based on calcite twin analysis in cores can reasonably be extrapolated away from drill holes. Such studies are consequently useful for predicting the geometry and the distribution of fracture patterns within the basin, although this aspect could not be discussed in the present paper.

More generally, the inverse analyses of calcite twins allow reconstruction of regional paleostress fields (orientations and magnitudes). These paleostress fields display high levels of consistency and homogeneity, and can be correlated with the main stages of the regional geodynamic evolution.

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