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Shear-sense determination on striated faults from *e* twin lamellae in calcite

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Abstract—In limestones, most fault planes are coated with calcite. The deformation of these calcite crystals is generally achieved by twinning on the *e* planes $\{01\bar{1}2\}$. The aim of this paper is to propose a rapid determination of the displacement sense on the fault planes by the study of the geometry of associated twinning. Calcite coatings have been sampled from faults for which the displacement sense is known. Thin sections perpendicular to the fault plane and parallel to the fault striation have been examined with an ordinary polarizing microscope. It is shown that in some crystals, the twin geometry leads unequivocally to a determination of the displacement sense. This is supported theoretically by the use of the right dihedron method. A figure summarizes the data for crystals which are twinned on one, two or three sets of twin planes.

Résumé—Les enduits de calcite qu'on trouve associés aux failles en terrain calcaire sont composés de cristaux xénomorphes, souvent déformés par maclage sur les plans *e* $\{01\bar{1}2\}$. On peut donc se demander s'il est possible de déterminer rapidement le sens de déplacement des failles par l'étude de la géométrie de ces macles *e*. Pour résoudre ce problème, nous avons échantillonné des placages de calcite sur des failles dont le sens de déplacement est connu. Des lames minces perpendiculaires au plan de faille et parallèles à la strie ont été étudiées à l'aide d'un microscope polarisant ordinaire. On montre que dans certains cristaux la géométrie du maclage est caractéristique du sens de cisaillement le long de la faille. La méthode des dièdres droits apporte une justification théorique et un tableau illustre le mode de raisonnement pour les cristaux présentant une, deux ou trois familles de macles.

INTRODUCTION

THIS PAPER presents new criteria for the determination of fault displacement from the analysis of calcite fault coatings.

In the upper part of the crust, faulting is generally associated with some continuous deformation and a reduction of porosity. At the microscopic scale, deformation in calcite is mostly achieved by a pressure-solution mechanism (Durney 1976, Gratier 1984) and by microtwinning on the *e* planes $\{01\bar{1}2\}$. So far, several dynamic analyses of twinning have been proposed (Turner 1953, Friedman 1964, Carter & Raleigh 1969, Laurent *et al.* 1981, Dieterich & Song 1984) which have given consistent results; most of them require many time-consuming measurements using a universal stage. At the macroscopic scale, preferred orientations of sets of contemporaneous striated faults may lead to the determination of part of the applied stress tensor (Bott 1959, Etchecopar *et al.* 1981, Etchecopar 1984). This is generally possible only if the sense of displacement can be determined for every fault. In limestones, and some other rocks (Petit *et al.* 1983), numerous reliable criteria have been described (Arthaud & Mattauer 1969, Hancock 1985) which have led to an interpretation of regional stress fields (Mattauer & Mercier 1980, Etchecopar *et al.* 1981).

In this paper, calcite twin geometry is used to define a simple and rapid method of shear determination which does not need statistical measurements. In a thin section parallel to the striation and perpendicular to the fault plane, twin traces (i.e. intersections between actual twin planes and thin section planes), are located with respect to striation direction *S*. It will be shown that the geometrical analysis of these data may be used to infer the shear sense on the fault plane. The basic assumptions are: (1) the stress field is supposed homogeneous (i.e. the direction of maximum compressive stress σ_1 has the same direction at the centre of the calcite crystal as around it); (2) twinning is contemporaneous with fault displacement; (3) the direction of displacement is parallel to the striae of fault coatings; (4) the sense of displacement does not vary with time; and (5) the host crystal does not rotate with respect to the fault plane during deformation.

SAMPLING

Calcite fault coatings are particularly well developed in calcareous argillaceous series. They appear as a thin wall with clear striations on both sides. Their width may be between about a millimeter and more than a decimeter. Although calcite fault coatings have been observed along all kinds of faults (reverse faults, thrusts, normal faults and strike–slip faults) only those associated with strike–slip faults have been taken into account in this paper. The method presented is based on the analysis of two series of samples: from the French external Alps in the vicinity of Orpierre (about 25 km north of Sisteron), and from the Cevennes fault in Languedoc (southern France). This is a major strike–slip fault trending about N045°E. Calcite crystallization and deformation are assumed to be contemporaneous with a Pyrenean (Middle to Upper Eocene) sinistral displacement of about 17 km (Bodeur 1976).

FAULT COATING STRUCTURES

All samples studied show a straight and continuous striation. Microstructures have been interpreted in a plane perpendicular to the fault plane and parallel to the striation, but thin sections perpendicular to both the fault plane and the striation have also been studied. In the fault coatings, most of the calcite crystals are anhedral and slightly deformed by microtwinning on the *e* planes $\{01\bar{1}2\}$. The extinction is generally sharply defined. Sometimes a shape fabric is defined by elongate fibres. The long axis of the fibres may be parallel or subperpendicular to the direction of striation according to the fault considered. In the former case, calcite shape fabrics are the same as those observed in shear fibre veins (Ramsay & Huber 1983). In the latter case, they resemble fabrics observed in tension-gashes. Shape fabrics are probably related to the real direction of displacement of the two fault tips, and to the kinetics of deformation. Antitaxial or composite fibres (Durney & Ramsay 1973, Ramsay & Huber 1983) are localized within bands parallel to the fault plane. The *c* axis fabrics within the fault coatings are generally consistent with shape fabrics: equant crystals show a random distribution of *c* axes, whereas in most fibres the optic axis is subparallel (0–35°) to fibre elongation. *e* twin lamellae appear generally as sharply defined straight lines which cross-cut the host crystal. When two sets of *e* planes are observed, the obtuse angle between them generally contains the minor axis of the intersection ellipse between the index ellipsoid of the calcite crystal and the thin section plane (i.e. the projection of the *c* axis in the thin section plane). Twin planes which are slightly oblique to the thin section plane appear as narrow bands which often differ from the host by abnormal coloration; accordingly, twin traces are less sharply defined. Calcite crystals which contain these oblique twins have not been used here for shear sense determination.

INTERPRETATION OF TWIN GEOMETRY

Attention will be focused on calcite crystals which show one to three twin sets (although they can be satisfactorily analyzed, untwinned crystals will not be taken into account here). The normal to the fault plane is *n* (*n* is oriented towards the outside of the fault coating). The trace of the optic axis (i.e. the intersection of the vertical plane containing the optic axis and the thin section plane), is *c*. Following Turner *et al.* (1954), twin sets are named e_1, e_2 and e_3 according to their relative abundance in a given crystal. Figure 1 summarizes the different attitudes of twin traces which can be interpreted for shear sense determination.

Interpretation is generally based upon the right dihedron method (Angelier & Mechler 1977) by considering twin planes as conjugate microfaults for which the shear sense is known (see Appendix). These 'microfaults' are assumed to make a high angle with the thin section plane, and the glide direction (i.e. twinning direction $[e_i : r_j]$ or $[(01\bar{1}2) : (\bar{1}101)]$) assumed to lie at a low angle to the direction of striation (S). This last point is verified if the two previous assumptions (i.e. *c* axis in the plane of thin section, and twin plane perpendicular to thin section plane) are satisfied (see Fig. A1).

One set of twin planes

Most calcite crystals which are twinned on only one set of twin planes cannot be used to infer the shear sense. Nevertheless, two particular cases can be considered (Fig. 1a–d). The first one concerns crystals for which the twin trace e_1 is perpendicular to the direction of striation S (Figs. 1 a & c). The optic axis makes an acute angle (α) with S (about 25°). Under crossed polarizers, and from the position shown in Fig. 1(a), a clockwise rotation of α leads to an extinction of the host crystal; the *c* axis is then east–west. This new position is the first extinction which is reached by the clockwise rotation of the thin section. In contrast, for Fig. 1(c), an anticlockwise rotation of α is necessary to reach the first position of extinction. These two figures correspond, respectively, to dextral and sinistral sense of shear along the fault plane. An interpretation using the compression and extension quadrants as defined by Angelier & Mechler (1977) can be proposed, provided the sense of twin gliding on e_1 is known (see Appendix): the quadrant containing *c* is the extension quadrant. The second case concerns the crystals for which the twin trace e_1 is parallel to S (Fig. 1b & d). The acute angle α between the *c* axis and the normal *n* to the fault plane is about 25°. It can be simply shown that the relative position of the optic axis with respect to *n* leads to the shear sense along the fault plane. Under crossed polarizers and from the position shown in Fig. 1(b) an anticlockwise or clockwise rotation corresponds, respectively, to dextral or sinistral sense of shear along S: shear senses along twin planes and along S are similar.

For these two particular cases, knowledge of the relative position of the *c* axis with respect to the normal to the fault is sufficient to infer the shear sense along S.

Interpretations of calcite crystals with an oblique set of twin planes e_1 can also be made if two or more crystals are taken into account. Figure 2 shows an example where compression and extension quadrants have been defined for two crystals. The sense of shear along twinning directions e_{11} and e_{12} is dextral and therefore the sense of shear along S is also dextral. The analysis using more than two crystals will not be further developed here.

Two sets of twin planes

Most crystals which present two sets of twin planes can be used to infer the shear along the fault plane. Both twin traces, e_1 and e_2, must be sharply defined optically; that is, only crystals for which the actual twin planes lie at a high angle to the thin section plane can be used. The angle β is defined as the acute angle between the two twin traces e_1 and e_2 (values of β fall between 0 and 65°, but are generally around 45°). It can be shown (Laurent

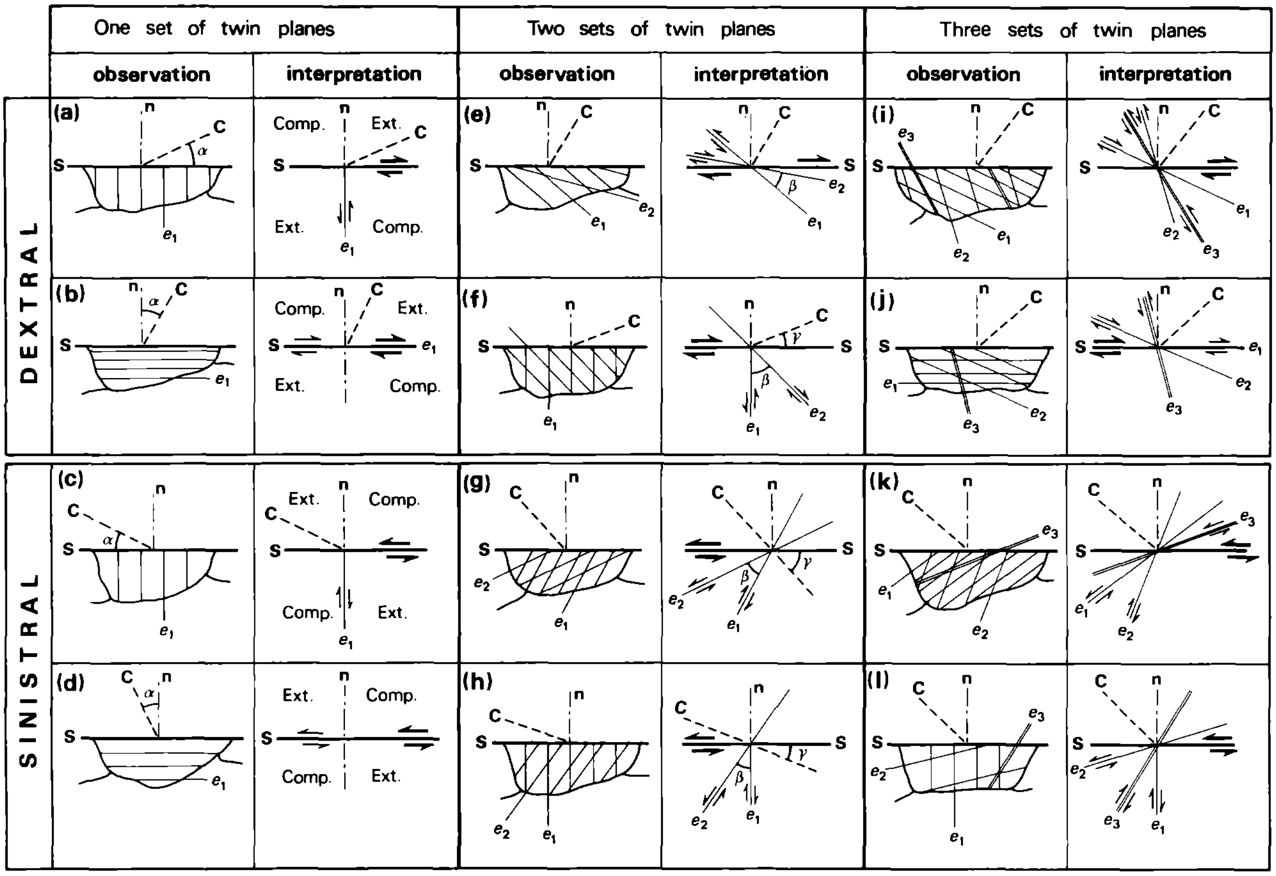

Fig. 1. Shear sense determined with a unique twinned calcite crystal. Plane of drawing contains the normal n to the fault and the direction S of striation. e_1, e_2 and e_3 are the twin traces. The broken line C is parallel to the direction of the vertical plane containing the c axis. Compressive and extensive quadrants have been drawn for calcite crystals which are twinned on one set of twin planes only. See text for details.

1984) that the trace of the optic axis is generally contained within the obtuse angle between e_1 and e_2. Conjugate displacement senses are therefore observed along the two twin planes and the acute angle between the two twin traces contains the direction of compression (see Fig. 3). Figures 1(e) & (g) show a twin geometry with the twin traces e_1 and e_2 inclined to the right (dextral shear sense) or to the left (sinistral shear sense). An interpretation of Fig. 1(e) using the right dihedron method (Angelier & Mechler 1977) is given in Fig. 3. Figures 1(f) & (h) illustrate situations where one of the two thin traces (here e_1) is perpendicular to the striae S; here the shear sense is given by the sense of inclination of e_2.

Three sets of twin planes

Crystals which are favorably oriented for twinning on the three e planes are those (Turner *et al.* 1954, Dietrich & Song 1984) for which the c axis is nearly parallel to the extension direction. Moreover, at least one of the three twin traces (e_3 in Fig. 1i–l) lies necessarily at a low angle to the thin section plane; consequently, the twinning direction on the edge [e_3: r_1] makes a high angle with the direction of striation S.

Calcite crystals with three twin traces are commonly observed in fault coatings. Interpretation of the geometry of twin traces relies on the two traces which lie at a high angle to the thin section plane (here e_1 and e_2). Therefore, as for Fig. 1(e)–(h), conjugate shear senses along e_1 and e_2 are observed, and the obliquity of the acute angle between e_1 and e_2 indicates the sense of displacement along S. This interpretation is consistent with the fact that the c axis lies in the extension quadrant (see Fig. 3). Figures 1(i) & (k) show two twin traces e_1 and e_2 which plunge to the right (dextral sense of shear) or to the left (sinistral sense of shear). In Fig. 1(j) & (l), e_1 is, respectively, parallel and perpendicular to the direction of striation S, and the inclination of e_2 to the right or the left is consistent with a dextral or sinistral sense of shear.

The above criteria should not be applied to crystals where at least two twin planes e_1 and e_2 are slightly oblique to the thin section plane; this is because actual twin directions make a high angle to the direction of striation, and a correct analysis would require the use of a universal stage. This last case is rather rare in the fault coatings studied.

DISCUSSION

The above shear-sense determination technique should only be applied to thin sections containing the displacement direction; that is, sections cut parallel to

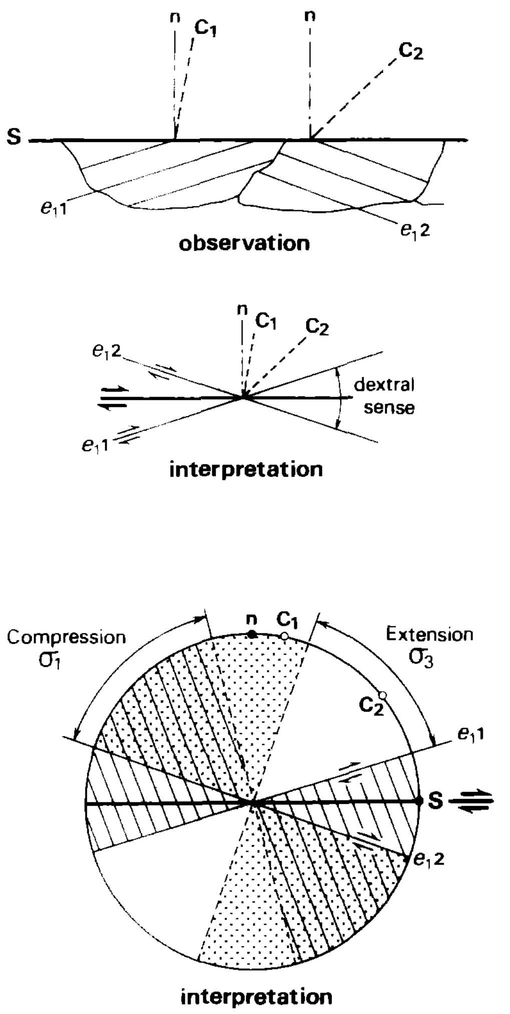

Fig. 2. Observation and interpretation of two twinned calcite crystals; each of them cannot be used separately to infer the sense of shear on the fault plane. (Same symbols as for Fig. 1). The relative position of the two optic axes c_1 and c_2 indicates a dextral sense of shear on the two twin planes e_{11} and e_{12}. Therefore, if the formation of the two twin planes is contemporaneous, a dextral sense of shear on the fault plane is unequivocally associated with this twinning. This is consistent with interpretation using the right dihedrons method (see text for details). The compression quadrant is hatched for crystal 1 and stippled for crystal 2.

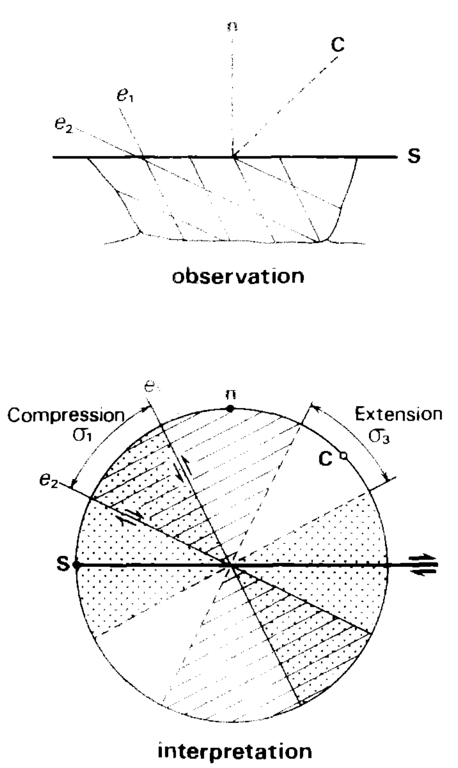

Fig. 3. Observation and interpretation of one single calcite crystal with two sets of twin planes e_1 and e_2. Both e_1 and e_2 are plunging to the right, indicating a dextral sense of shear (see also Fig. 1e). Plane of drawing, conventions for the projection and symbols as for previous figures.

the fault striation and perpendicular to the fault plane. In these sections, most of the calcite crystals (about 90%) which can be interpreted individually lead to the correct shear sense along the fault plane. Nevertheless, it must be pointed out that some crystals (a few per cent) may give the wrong result. This anomaly probably results from inhomogeneous stress, but twin lamellae may be also primary twins which do not result from deformation contemporaneous with fault displacement. This emphasizes that the determination of a reliable sense of shear requires at least 5–10 calcite crystals.

The method proposed in this paper has been applied successfully to two types of structures: shear fibre veins from Languedoc and calcite cement in faulted pelitic sandstones from the Triassic series of Morocco. The consistency of the results obtained, compared with other classical criteria (Petit *et al.* 1983), lends valuable support to this rapid method of determination. This method could be suitably applied to other examples, particularly where other shear criteria are lacking.

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APPENDIX

The geometry of e *twinning in calcite*

Twinning of calcite was extensively studied more than 30 yr ago (Handin & Griggs 1951, Turner *et al.* 1954). From a geometrical point of view and for a given crystal, the *e* twin lamellae $\{01\bar{1}2\}$ are similar to microfaults for which the five constitutive parameters (i.e. direction, plunge, pitch, sense of movement and value of real displacement), are all imposed by crystallography.

Each calcite crystal has three symmetrically equivalent twins e_1, e_2 and e_3 (Fig. A1). The angle between the optic axis (c axis) and the normal to a twin plane is about 26.5°. For a twin plane e_i, the twin direction is along the edge $[e_i:r_j]$. The planes which contain both the optic axis and the normal to a twin plane $[e_i]$ also contain the direction of twinning $[e_i:r_j]$ (Fig. A1). Figure A2 shows the geometry of a twin lamella when viewed in a section perpendicular to twin plane and parallel to twin direction. The width of twin lamellae associated with brittle deformation is about a fraction of a micron (Groshong 1974; see also Barber & Wenk 1976 and Goetze & Kohlstedt 1977). Therefore, when dynamic interpretation is carried out, there is no possibility of confusion between the host and the twinned part of the crystal (Friedman 1964).

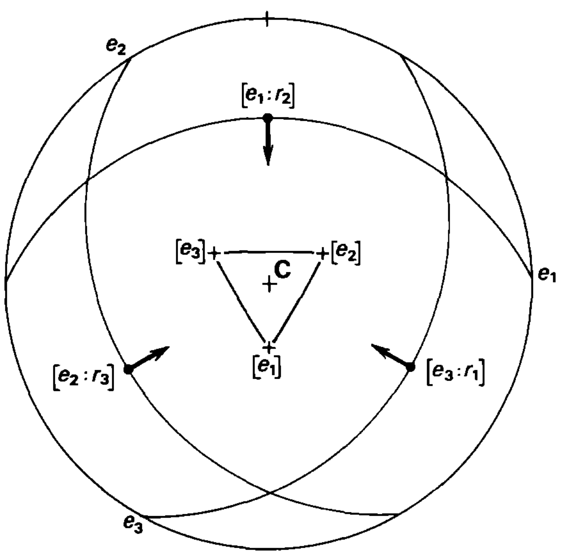

Fig. A1. Stereographic projection (lower hemisphere) of calcite twin planes $\{10\bar{1}2\}$. The optic axis c is vertical, at the centre of the diagram. Poles to the three sets of twin planes are $[e_1]$, $[e_2]$ and $[e_3]$. Planes of twinning are great circles e_1, e_2 and e_3 which contain directions of twinning $[e_i:r_j]$. For each twin plane, the arrow is parallel to the twinning direction; its head indicates that the upper part of the crystal moves upwards, towards the c axis, like a reverse microfault.

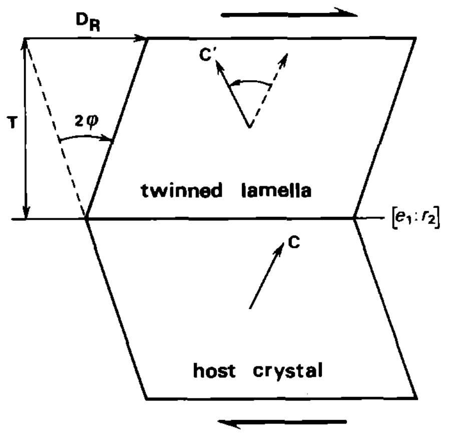

Fig. A2. The geometry of e twinning in calcite. The plane of the drawing is perpendicular to the twin plane e_1 and contains both the direction of twinning along the edge $[e_1:r_2]$ and the optic axes (c for the host crystal and c' for the twinned lamella). From the host crystal, the deformation is achieved by simple shear on the composition plane with a shear angle $2\varphi = 38.3°$. Thickness of twin lamella is T and total displacement is D_R. Notice that the rotation of the optic axis (c to c') is anticlockwise for a dextral sense of shear.