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Calcite twins, their geometry, appearance and significance as stress–strain markers and indicators of tectonic regime: a review

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Abstract—Twin lamellae are a widespread feature in calcites of any type and origin. Twinning in calcite is an important intracrystalline deformation mechanism with low critical resolved shear stress and virtually no temperature dependence. In contrast to most slip systems in rock-forming minerals, twinning therefore permits intracrystalline deformation at very low temperature and very little confining pressure. Twinning alone, however, cannot lead to large strains because only one independent slip system is effectively available. Twins lead to discontinuous shearing on the grain scale which gives rise to considerable strain incompatibilities at grain boundaries. Twinning consequently leads to strain hardening. Detailed observations of the geometry of twin lamellae show that incompatibilities at grain boundaries are eliminated by pressure solution on the grain scale at low temperature and dynamic recovery processes at higher temperatures.

Twins are found in various tectonic environments and record very small strains in rocks deformed under very little cover. Different twinning strain and twinning stress methods and palaeopiezometers are critically reviewed. All methods are limited to strains of less than 15% shortening (or extension) by twinning. Twinning nevertheless is an important, although not directly measurable, contribution to the total strain in highly strained calcite rocks at least up to middle greenschist facies, under which conditions it is the most effective contributor to the formation of strong lattice preferred orientations in calcite tectonites.

The appearance of calcite twin lamellae changes systematically as a function of deformation temperature. Micro-twins and straight narrow ($<1\,\mu$m) lamellae are characteristic of very low temperatures where no other slip system competes and where the absence of effective recovery mechanisms prohibits large strains by twinning. Above *ca* 150°C, thicker (>1–$5\,\mu$m) but fewer twins are developed. Above approximately 200°C, curved twins, twinned twins and completely twinned grains indicate the progressive importance of other slip systems, and larger intracrystalline strains are possible. At *ca* 250°C and above ancient straight twin lamellae are modified into irregular geometries by recrystallization and grain-boundary migration. The appearance of calcite twins is proposed as an approximate but rapid and easy-to-use geothermometer in low-temperature environments.

INTRODUCTION

CALCITE twins have long been recognized as a deformational feature, and precise crystallographic laws have been determined for the so called *e*-twin-lamellae in the last century (e.g. Rose 1868, Mügge 1883, Klassen-Neklyudova 1964, Barber & Wenk 1979, Wenk *et al.* 1983). Twins have been widely applied in tectonic studies since Weiss (1954) and Turner (1962) developed a method to determine stress axes from a population of *e*-lamellae in deformed calcite rocks. This 'dynamic' method has been modified and refined in order to determine the principal directions and/or magnitudes of either (palaeo-)stress or strain (Groshong 1972, Spang 1972, Jamison & Spang 1976, Tullis 1980, Laurent *et al.* 1981, 1990, Pfiffner & Burkhard 1987, Rowe & Rutter 1990, Lacombe & Laurent 1992).

Twinning strain analyses were first applied to high-grade marbles (Turner 1953, Turner & Weiss 1963) in which the observable twins are mostly late and tectonically quite insignificant as compared to the metamorphic history and associated high strains (e.g. Turner & Orozco 1976). Twin strain methods were subsequently applied to unmetamorphosed, macroscopically undeformed or very weakly deformed cover rocks, in which regionally meaningful palaeostress axes directions have been determined (e.g. Friedman & Conger 1964, Nissen 1964, Groshong 1972, Groshong *et al.* 1984a,b, Burkhard 1986, Craddock & Van der Plujim 1988a, Jackson *et al.* 1989, Mosar 1989, Tourneret & Laurent 1990, Tschanz 1990, Ferrill 1991, Sommaruga 1991, Lacombe & Laurent 1992 and many references therein). In very low grade rocks, twinning strain may be the only discernible or measurable intragranular deformation and careful analysis of it has helped to elucidate the mechanics and kinematics of fold and thrust formation (Geiser 1988, Groshong 1988, Kilsdonk & Wiltschko 1988, Evans & Dunne 1991). Twinning strain analyses have also been successfully applied in microstructural studies of very weakly deformed calcite rocks (e.g. Teufel 1980, Craddock & Van der Pluijm 1988b, Hudleston & Tabor 1988).

The purpose of this paper is to review the significance of twinning in calcite as a deformation mechanism in various tectonic environments, ranging from very weakly deformed cover rocks to highly strained calc-mylonites deformed under lower greenschist facies conditions. The existing methods of twin strain and twin stress analysis are critically reviewed. Special emphasis is placed on the significance of different types of twins as potential indicators of temperature and deformation regime in very low grade calcite rocks.

The conclusions of this paper are drawn from a series of deformation studies conducted at Neuchâtel University over the last 10 years. Calcite deformation features have been analysed in different portions of a cross-

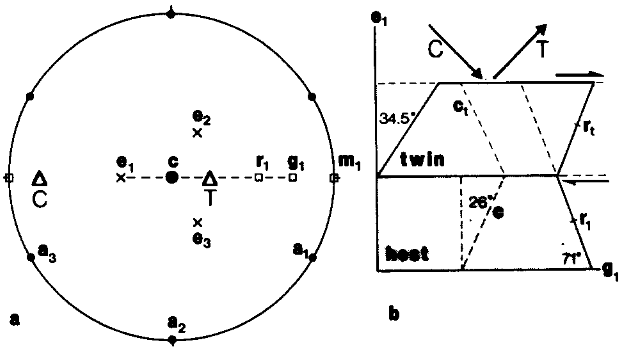


Fig. 1. The geometry of calcite *e*-twinning. (a) Equal-area projection of the principal axes (c, a_1, a_2, a_3) of calcite and a selection of important crystallographic planes (poles): twin planes e_1, e_2 and e_3, glide direction g_1, rhombohedral plane r_1 and prismatic plane m_1. Optimum compression C and tension T axes for twinning on e_1 are indicated. The section represented by the dashed line g_1–r_1–T–c–e_1 (to be imagined in the upper hemisphere) is shown in (b). (b) Schematic representation of an *e*-twin shown in an e_1–g_1 cross-section (dashed line in stereogram) through host (stippled) and twin, showing the angular relationships between the major crystallographic elements, and the optimum compression C and tension T axes for twinning on e_1. Shear strain for an individual twin is $\gamma = \tan(34.5°) = 0.687$; this angle is represented on the left-hand side, whereas to the right, the twinned position (r_t) of the trace of an r_1 (or r_2) cleavage plane is shown.

section through the Alps. The cross-section includes the Plateau and folded Jura (Tschanz 1990), the Pennine Prealps (Mosar 1989), the Helvetic nappes (Groshong *et al.* 1984b, Burkhard 1986, 1990), the Pennine nappes of the Central Alps (Mayerat 1989) and the Southern Alps (Sommaruga 1991). Deformation temperatures range from surface conditions in the Jura to lower greenschist facies in the southern Helvetic nappes and middle greenschist facies in the Pennine area.

GEOMETRIC OBSERVATIONS ON TWIN LAMELLAE

Crystallography of calcite twins

Calcite twins are easily produced on pure single crystals by hand with a pocket knife (e.g. Klassen-Neklyudova 1964, p.59). This and their obvious appearance in thin sections made them an early topic of research in crystallography, and the precise geometry and 'laws' of mechanical *e*-twinning have been known for more than a century (Rose 1868, Baumhauer 1879, Mügge 1883). The principal planes and crystallographic elements of calcite are illustrated in Fig. 1(a) (Turner & Weiss 1963, p.238, Wenk 1985, table 1). For the sake of completeness, it should be mentioned that twinning in calcite has also been reported on *r*-planes (in a positive shear sense). This paper deals only with the more common *e*-twins, here loosely termed 'calcite twins' or just 'twins'. *e*-planes are mirror planes between host and twin (Fig. 1b). Due to the trigonal symmetry of calcite, three different *e*-, *r*-, *g*-, etc., poles exist per crystal unit. In terms of deformation, an individual *e*-twin can be considered as a zone of perfect simple shear (compare Figs. 2 and 8f) with known shear direction [*g*], known shear sense (positive by convention) and known angular shear (34.7°). The amount of simple shear deformation in any twinned crystal is directly proportional to the thickness of the twinned portion in this crystal. Since there is an angle of 52° between the orientations of the host *c*-axis and twin *c*-axis, twins are easily recognized under a polarizing microscope. Optical microscopy (combined with a Universal-stage for precise spatial measurements) is therefore the most convenient means of observation.

Submicroscopic details of the twinning have been studied by means of dislocation etch pits on cleavage surfaces (Keith & Gilman 1960, Klassen-Neklyudova 1964, p.177ff.), by X-ray topography (Sauvage & Authier 1965) and TEM observations (e.g. Barber 1985, Meike & Wenk 1988). In summary, these studies have confirmed the macroscopically determined twinning law and allowed Motohashi *et al.* (1976) to propose a sort of dislocation glide mechanism for twinning. Partial dislocations associated with twinning have by far the shortest Burger's vector (1.27 Å) and smallest Peierl's potential of all known glide systems in calcite. This may explain the ease of twin gliding (very low critical resolved shear stress, weak temperature dependance) in terms of dislocation theory.

Appearance of calcite twins: thin, thick, straight or sutured?

Different types of *e*-lamellae can be distinguished in naturally and experimentally deformed rocks (e.g. Weiss 1954). A first characteristic feature of twins is their thickness. On the one hand, very thin *e*-lamellae without microscopically visible twinned material (<1 μm, termed microtwins by Groshong 1972), could on first sight be mistaken as cleavage planes. Thick twins on the other hand (i.e. thicker than about 1–5 μm) are unmistakably recognizable as *e*-twins in thin section. From both laboratory and field observations many authors have concluded that the thickness of twins is mainly a function of deformation temperature (e.g. Groshong *et al.* 1984b, Rowe & Rutter 1990, Ferrill 1991). Although the thickness of a twin is a direct measure of (shear-) strain, a given amount of deformation in a calcite grain could be distributed either within many thin twins, or alternatively within a few thick twins (Fig. 2). For instance 100 microtwins each 1 μm in width result in 100 μm of twinned crystal that could as well be located within a single twin or just a few thick twins. Compared to other slip systems microtwinning would seem to be much better adapted to produce 'homogeneous' deformation on the grain scale because thick twins lead to larger steps in the grain boundaries and therefore cause more space problems with neighbouring grains (Fig. 2).

A possible reason for the formation of thick twins, rather than thin (micro-) twins, at elevated temperatures could be the stress dependence of twinning. The formation of twins is considered as a two step mechanism: (1) nucleation, which needs a minimum stress concentration; and (2) growth, that is enlargement of an existing thin twin (not to be confused with twin boundary migration—which is not a deformation mechanism). Depending on temperature, shear stress, confining pressure, etc., and therefore on the ease of other slip systems and recovery mechanisms in the aggregate, enlargement of an existing twin could be easier than the initiation of a new one (Sauvage & Authier 1965, Barber 1985, p.165). Alternatively, the competition between thin twins and thick twins could also be related to the surface energy of the (twin-) grain boundary: the development of larger twins, rather than many small ones, minimizes surface energy.

Thick twins produced in laboratory experiments at elevated temperatures ($>$400°C) are typically lens-shaped, with constrictions toward grain boundaries (e.g. Schmid in Ramsay & Huber 1983, fig. 7.14, Rowe & Rutter 1990, fig. 1). Similar features are less frequently observed in nature where twins mostly remain thick up to the grain boundaries (Figs. 8d and 9a & f). There could be many reasons for this difference. (a) In naturally deformed rocks, dissolution–crystallization along grain boundaries, governed by stress differences, may help to remove geometric incompatibilities and thereby prevent intense elastic deformation and the formation of cracks and fractures. (b) Twin-boundary migration (driven by the elastic deformation around the twin tip) may tend to create rectified grain boundaries. (c) Grain-boundary migration may remove most of the constrained twin tips, again, driven by stored energy within elastically deformed regions. In case (a) there is a clear difference between laboratory (dry, fast) and natural (wet, slow) deformation whereas in cases (b) and (c) it is less obvious why natural and laboratory deformations should produce any significant difference in appearance of thick twins.

Another important observation concerns the geometry of the twin boundary. During formation, a twin boundary forms a well defined smooth surface within a calcite crystal as given by the twinning law. Smooth, but curved twin boundaries can be attributed to either elastic deformation of the twin and/or host (visible through undulous extinction) or, alternatively, result from intracrystalline deformation such as by *r*- or *f*-glide (Turner & Orozco 1976). Since the critical resolved shear stresses for both *r*- and *f*-glide and other slip systems is strongly temperature dependent (Wenk 1985, fig. 2, De Bresser 1991, fig. 4.9), the observation of curved twins, as evidence for the activity of intracrystalline slip systems other than twinning, can qualitatively be correlated with either temperature or shear stress.

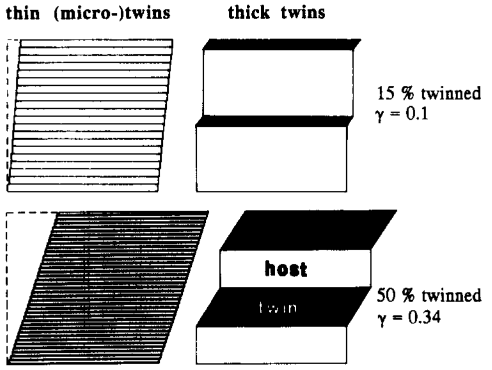


Fig. 2. Schematic diagram illustrating the difference between thin and thick twins, twin density (number of twins per mm) and percentage volume fraction of twin lamellae. In two cases, exactly the same amount of shearing by 15% ($\gamma = 0.1$) and 50% ($\gamma = 0.34$) twinning, respectively, is distributed either relatively homogeneously into many thin twins or, alternatively, very inhomogeneously into just a few thick ones—the latter case causing larger steps in the grain boundary.

Irregularly shaped, sutured and bulged twin boundaries result from twin-boundary migration recrystallization (e.g. Vernon 1981). The recognition of this is facilitated on twin boundaries, which are known to be smooth during twin formation. Grain-boundary migration is primarily driven by differences in stored energy between neighbouring grains. This thermally activated process is strongly temperature dependent and the presence or absence of grain (or twin) boundary migration may be used as a textural thermometer to indicate maximum temperature.

Twin-grain boundary and twin–twin interrelationships

Twinning leads to very inhomogeneous deformation on the grain scale and geometric complications arise both at grain boundaries (Fig. 2) and at twin–twin intersections (Fig. 4). A natural example is illustrated in Fig. 3 (photograph in Fig. 9a): a considerably strained calcite grain is graphically retrodeformed into its presumed initial shape (twinned portions of the crystal are shown in white and are identified as such because of their slightly lens-shaped tapering toward the grain boundary. Both the deformed and the retro-deformed grains are characterized by many angular steps in the grain boundaries (circled in Fig. 3). It is very unlikely that such steps existed prior to (twinning) deformation of the grain. Grains on both sides of the boundaries had to undergo dissolution–crystallization in order to prevent the creation of open spaces during deformation. An alternative interpretation would be to assume grain boundary migration. In the case shown in Fig. 3, however, in which deformation occurred at around 200°C, there is no evidence for this. A similar conclusion is reached in the case illustrated in Fig. 8(d) in which it is impossible to unstrain the two heavily twinned grains and at the same time conserve a tight joint along the grain boundary. On the other hand, an example of grain-boundary migration post-dating twinning is illustrated in Fig. 8(e): twins are either 'truncated' by a migrated boundary or 'left behind' in a twinned grain. The abrupt termination of several twins within this grain is interpreted as a former position of this grain boundary.

Calcite crystals often display two or three sets of twin planes (Fig. 7). From the twinning law it is clear that twinning on more than one set of *e*-planes within a single crystal must lead to strain incompatibilities at twin–twin intersections (Fig. 4). Rose (1868) observed the formation of so called Rose-channels ('hohle Canäle') at such intersections in calcite crystals deformed at room temperature. Such voids are not easy to observe in thin

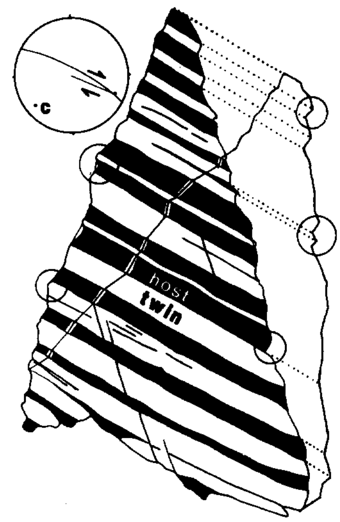


Fig 3. Natural example of a calcite grain, considerably deformed by twinning on a single set of thick twins (drawn from a microphotograph, see Fig. 9a). Twins (white) are identified as such by their slightly lens-shaped constrictions toward the grain boundary. The calcite grain is graphically retrodeformed into its presumed original shape. Very angular steps in both the present and the retrodeformed grain boundaries are circled. Such steps are a consequence of twinning deformation and their impingement (on the left-hand side) requires dissolution–crystallization deformation along the grain boundary in order to prevent the formation of voids. The stereogram in the upper left-hand corner shows the crystallographic orientations of the *c*-axis of the host, the *e*-lamellae (great circle) and the inferred shear direction.

sections of natural samples deformed at low temperature—if they existed, they may have been rapidly sealed by secondary calcite precipitated from a fluid. In samples deformed at higher temperatures the develpment of thicker twins facilitates observations, but voids are even less likely to survive in these rocks. Twins within twins are either rational, in correct crystallographic position and therefore late with respect to the host or, alternatively, irrational, that is passively deformed by twinning of the 'hosting twin' (Fig. 4). The geometric relations at the intersection of two twin sets thus permits the determination of a relative chronology (Turner & Orozco 1976). An example of a first twin, passively sheared by twinning on a second twin plane, is shown in Fig. 8(f). The first twin is said to be in an irrational position within the second twin. Deformations necessary to accommodate this passive rotation lead to the development of internal twins within the first set but, for strain compatibility reasons, glide on other systems or elastic deformation is also necessary. Geometric complications at twin–twin intersections are comparable to those at the intersection of faults of two conjugate sets. Even though a relative chronology can be deduced in most cases, the timing of the two twins (conjugate faults) is usually considered as contemporaneous on a geologic time scale.

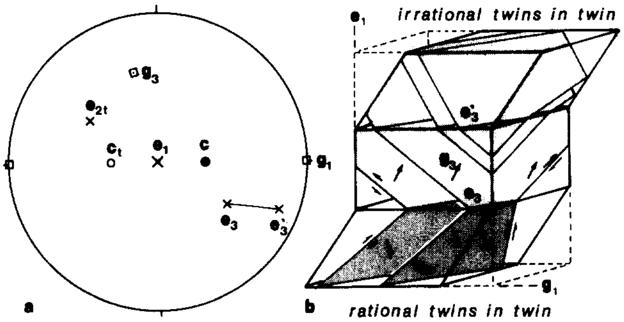


Fig. 4. Interrelationships among calcite twins. Twins in twins are either rational or irrational (Turner & Orozco 1976). (a) Equal-area projection (upper hemisphere) of crystallographic elements relevant to the discussion of twin–twin relationships. (b) Block diagram illustrating the spatial relationships between twins: an initially rectangular block of a calcite crystal (dashed line) is twinned on e_1 in its upper and lower thirds. e_1–thick twins (upper and lower thirds of block); c–c-axis of host; c_t–c-axis of thick twin e_1; e_3—rational thin twins (in crystallographically correct position) within host calcite; g_3—twin glide direction of e_3 twinning (shear sense is indicated in the block diagram); e'_3—irrational position of twin lamellae e_3 within e_1 twin (upper third of block), e'_3 formed before e_1; e_{2t}—rational thin twins within thick twin e_1 (represented in lower third of block), e_{2t} formed after e_1, shear sense and glide direction of e_{2t} are indicated in block diagram.

Late rational twins often meet each other along twin boundaries (Figs. 8a & b). This is interpreted as being due to stress concentrations at the twin tips. Again, crystallographically, this has to lead to strain incompatibilities. Shear on the two twins meeting each other is not compatible (Fig. 4), and accommodation by other mechanisms is needed to prevent the formation of voids. Note that highly strained calcite grains usually display only one set of twins (Fig. 10) (see also Schmid *et al.* 1987).

TWIN TYPE AS AN INDICATOR OF MAXIMUM TEMPERATURE AND DEFORMATION REGIME

It is tempting to use the appearance of twins to estimate deformation temperatures, even though there is no precise knowledge of all processes leading to the contrasting twin types. Below, a correlation of twin type with deformation temperature is presented. Correlations are based on observations in the Helvetic nappes of western Switzerland (Figs. 5–7). These nappes represent a classic area where both the calcite deformation and the very low grade metamorphism have been extensively studied (Schmid 1982a, Dietrich & Song 1984, Burkhard 1986, 1988, 1990, Burkhard & Kerrich 1988, Burkhard & Kalkreuth 1989). Maximum temperatures of deformation in this profile are well constrained from the use of several independent thermometers (modelling of vitrinite reflectance data, stable isotope thermometry ($\delta^{18}0$), calcite–dolomite thermometry), yielding absolute temperatures at several points in the profile (Fig. 5). Interpolations between these points are constrained by over 200 illite crystallinity measurements and the first appearance or disappearance of index minerals like glauconite–stilpnomelane, pyrophyllite–chloritoid and prehnite–pumpellyite–actinolite (Burkhard 1986, figs. 12 and 13). Four different types of twins have been distinguished and 'mapped' in this cross-section using over 150 thin sections (Fig. 5). A very good correlation between 'first appearance' of types III and IV twins and 'metamorphic isograds' is observed. Exceptions are present, however, in major thrust zones and normal fault zones, where bending and recrystallization of twins (type III and IV) is observed at significantly

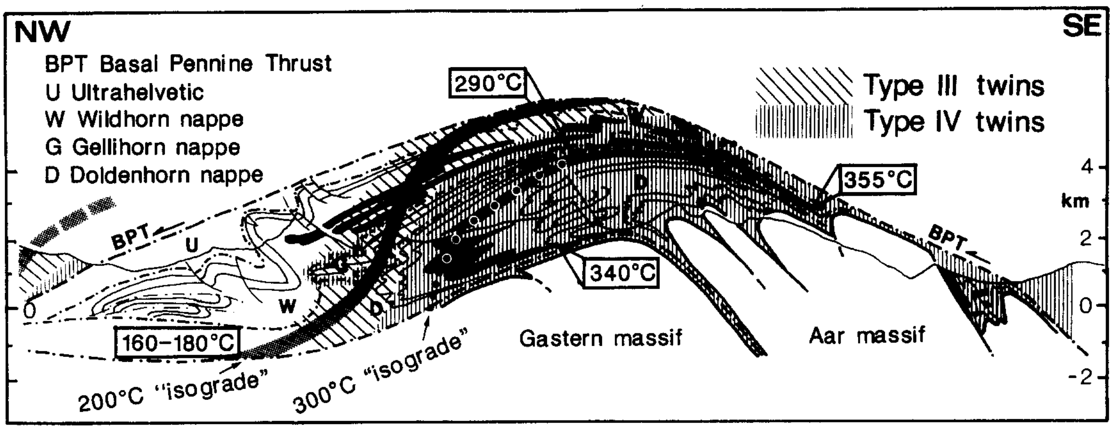


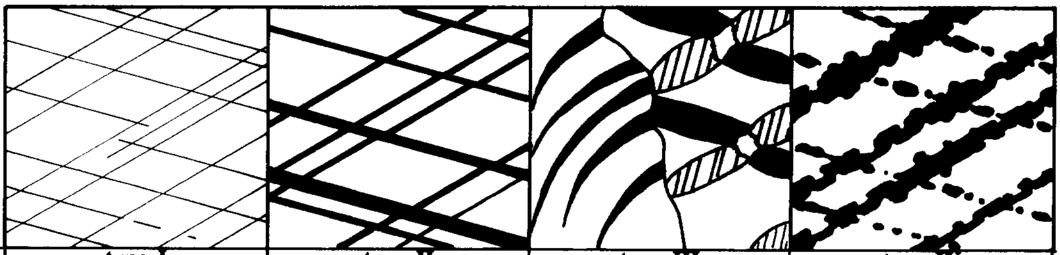
Fig. 5. Cross-section of the Helvetic zone at the western end of the Aar massif, Switzerland. Only major tectonic and stratigraphic units are distinguished; the black layer is Malm-limestone. Maximum temperatures and interpolated metamorphic 'isograds' are drawn according to Burkhard (1988) and references quoted in the text. Two different superimposed shadings indicate where twins of type III and type IV are common. Type I and type II twins can be found all over the cross-section—they are the only intracrystalline deformation in the northwest, but represent late, post-metamorphic deformation in the southeast.

lower metamorphic grade than within 'representative', moderately deformed, country rocks. The most typical features are summarized in Fig. 6, where an interpretation in terms of deformation temperatures is given. Examples are presented in Fig. 7. Care has to be taken with Fig. 6 because all the information comes from a single mountain chain with its own particular deformation–burial history. Similar conclusions, however, have been reached in the Appalachians (Groshong 1988, Evans & Dunne 1991). The reasons for the observed relationship between twin type and deformation temperature is not well understood. Factors which influence twinning (e.g. differential stress, strain, strain rate, grain size, grain orientation) are not necessarily responsible for the *type* of twins developed. Twin type is thought to be mainly a function of deformation temperature, and only to a minor degree dependent on differential stress and/or strain rate. Since calcite twinning is a very widespread feature in any, even slightly deformed, terrane, observations made on the appearance of calcite twins represent an easy-to-use and rapid means of estimating maximum deformation temperatures.

TWINNING AS A DEFORMATION MECHANISM

The twin glide system

Although the terms 'glide' and 'slip' are used in a restrictive sense to describe the gliding of dislocations, twinning too in a larger sense can be regarded as an intracrystalline glide system. According to Sauvage & Authier (1965) and Motohashi *et al.* (1976), twinning is a true, if somewhat complex dislocation glide mechanism. The main difference between twinning and other glide systems (*r*-, *f*-, etc.) lies in the fact that portions of the crystal deformed by twinning change their crystallographic orientation, not only passively with respect to



	type I	**type II**	**type III**	**type IV**
Geometry **Description**	- thin twins - straight - rational - 1, 2 or 3 sets per grain	- thick (>>1μm) - straight - slightly lense shaped - rational	- curved thick twins - twins in twins - completely twinned - irrational	- thick, patchy - sutured twin boundaries - trails of tiny grains - irrational
Interpretations	- little deformation - little cover - very low temperature - (post-metamorphic) - (late tectonic)	- considerable deformation - completely twinned grains are possible - syn- or post-metamorphic deformation	- large deformation -intracrystalline deformation mechanisms (r-& f-glide) - syn-metamorphic deformation.	- large deformation - dynamic recrystallization (grain boundary migration) - pre- or syn-metamorphic deformation
Temperature	**< 200°C**	**150-300°C**	**> 200°C**	**>250°C**

Fig. 6. Classification of twins according to their appearance in thin section. Four different types of twin are distinguished and interpreted in terms of deformation temperature and mechanisms (cf. Weiss 1954, Ferrill 1991).

external co-ordinates but also quite drastically by a complete internal twisting of the twinned crystal portion. This twinning law has two severe consequences for the aggregate deforming by twinning.

(1) As soon as twinning has taken place in a given grain, this grain cannot be regarded as a single crystal anymore for internal deformation on slip systems other than the activated *e*-lamella. In fact the initial grain is now composed of twice as many lamellar 'crystals' than twins that have been formed. For continued deformation, this once single grain behaves now as a composite grain with portions of different crystallographic orientation. Of the three initial independent *e*-twin-glide systems in the sense of von Mises (1928) only a single-system remains available for continued deformation. Additional slip systems (*r*-, *f*-, etc.) are no longer able to act through the entire grain but are confined to each single crystal lamella. The rheologic consequence of this is not easy to predict: on the one hand, intuitively, strain hardening might be expected because twin lamellae hinder each other in their development and lead to microcracks (Rose 1868). In strongly and repeatedly twinned material this means a volume increase and an embrittlement of the material. On the other hand, the formation of many twin lamellae could also be regarded as a grain size reduction which could either increase the strength of the rock at low temperatures (Olsson 1974) or lead to strain softening at higher temperatures (i.e. Schmid 1982b).

(2) Twinning clearly leads to inhomogeneous deformation on the grain scale. Geometric incompatibilities arise at grain boundaries and twin–twin intersections (Fig. 2). In comparison, *r*-slip and *f*-slip do not leave any visible traces and deformation may be considered homogeneous on the grain-scale. The latter would thus seem much better adapted to produce homogeneous deformation of the aggregate, even if the number of glide systems is still too small to allow for truely homogeneous strain in each grain. Both these characteristics strongly influence twinning as a deformation mechanism and the rheology of the aggregate.

The twinning regime

Deformation regimes are characterized by the relative contribution of different deformation mechanisms to the bulk deformation of an aggregate. Intracrystalline glide systems in crystals are characterized by their crystallography and a critical resolved shear stress (τ_c) necessary to activate slip. Competition among glide systems is governed mainly by the difference in τ_c values associated with each system, and these in turn vary as a function of temperature but also, to a certain degree, of grain size, differential stress, strain rate, etc. Values of τ_c are determined experimentally on single crystals (Handin 1966, Wenk 1985, table 1, De Bresser 1991). For calcite crystals and rocks it has been found that *e*-twin gliding is by far the easiest slip system (with the lowest τ_c value) up to temperatures of at least 800°C (De Bresser 1991, fig. 4.9). From this, one would expect twinning to be an important deformation mechanism at all temperatures. However, of all glide systems, twinning is the least temperature sensitive and, therefore, its importance compared to *r*- and *f*-slip decreases with increasing temperature. Based on observations on naturally deformed rocks and twin strain analyses, some authors (e.g. Groshong *et al.* 1984b) have proposed that twinning could cease to be a competitive deformation mechanism at higher temperatures (above 300°C). Since twinning apparently needs stress concentrations for twin nucleation, twinning could cease to be competitive when insufficient stress concentrations are built up, for example because unfavourably oriented 'indentor' grains are removed by recrystallization. However, from the crystallographic preferred orientations of naturally deformed limestones it would seem that *e*-twinning still acts at higher temperatures (Schmid *et al.* 1987). Taylor–Bishop–Hill calculations have great difficulties in modelling *e*-twinning because *c*-axes within twins are twisted (not just passively rotated) with respect to the original grain and because grains are subdivided into several smaller grains by twinning. Even so, Taylor–Bishop–Hill calculations without any contribution of *e*+ (twin-) glide do not simulate the textures of experimentally deformed calcite rocks at high temperatures (Wagner *et al.* 1982, Wenk 1985, pp. 374–375). This could signify that twinning, even if not easily visible (obliterated by recrystallization?), is still a significant glide system at higher temperatures. Schmid *et al.* (1987, p. 762ff.), in limestones deformed experimentally at high temperatures, found textures which they attributed to *r*-, *f*- and basal-gliding alone. Corresponding textures, however, have never been identified in naturally deformed rocks (Schmid *et al.* 1987, p. 774). In conclusion it seems that even in the absence of obvious twins, twinning is an important (if not the most important) contributor to the strong *c*-axis point maxima found in many naturally deformed calcite tectonites, at least up to middle greenschist facies. Schmid *et al.* (1987) have called this the twinning regime.

TWIN LAMELLAE AS A STRESS–STRAIN GAUGE

Stress or strain?

All methods are based on the crystallographic twinning law and only rational twins (types I and II) are suitable for stress–strain analyses. All methods make the tacit assumption that the measured twins formed in a single stress field and that twins were not passively rotated after formation. Large or non-coaxial deformations necessarily lead to incompatible orientations of twins and conclusions are difficult to draw from such twin data sets. These methods will therefore always be limited to very small strains which can be approximated by coaxial conditions. In this sense, the distinction between stress and strain is somewhat academic—clearly, all methods are based on some measurable

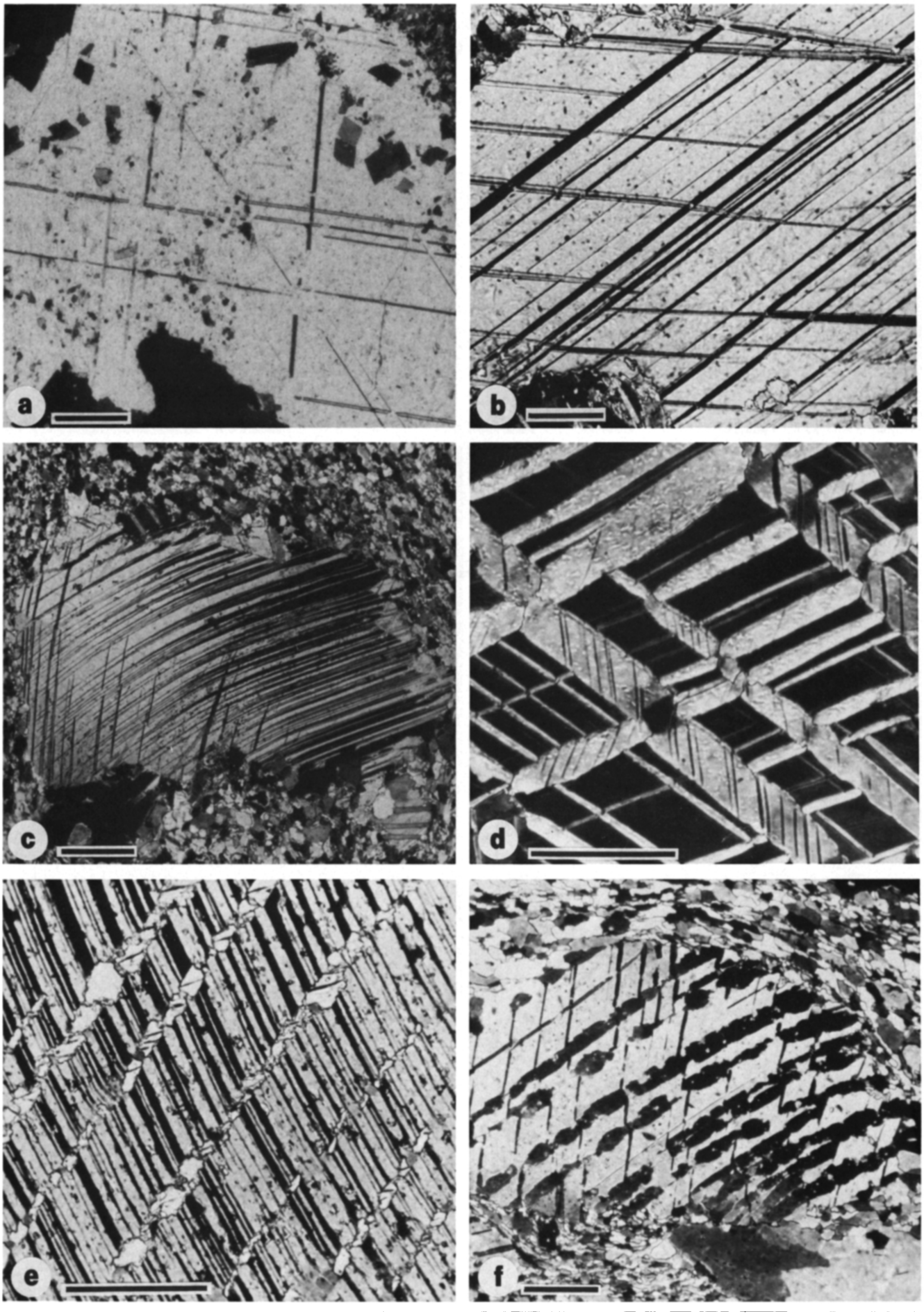


Fig. 7. Representative natural examples of twin types shown in photomicrographs of ultrathin sections (<5 μm thickness) in crossed polars. All scale bars are 20 μm. (a) Type I: three sets of thin rational twins in vein calcite. (b) Type II: two sets of thick (>5 μm) rational twins. (c) Type III: bent twins; the right part of the grain is almost completely twinned. (d) Type III: twinned twins. Thin rational twins within thick twins. (e) Type IV: trails (NE–SW) of recrystallized grains are interpreted as former thick twins. (f) Type IV: thick twins show irregular, sutured boundaries—interpreted as the result of grain-boundary migration, post-dating twinning.

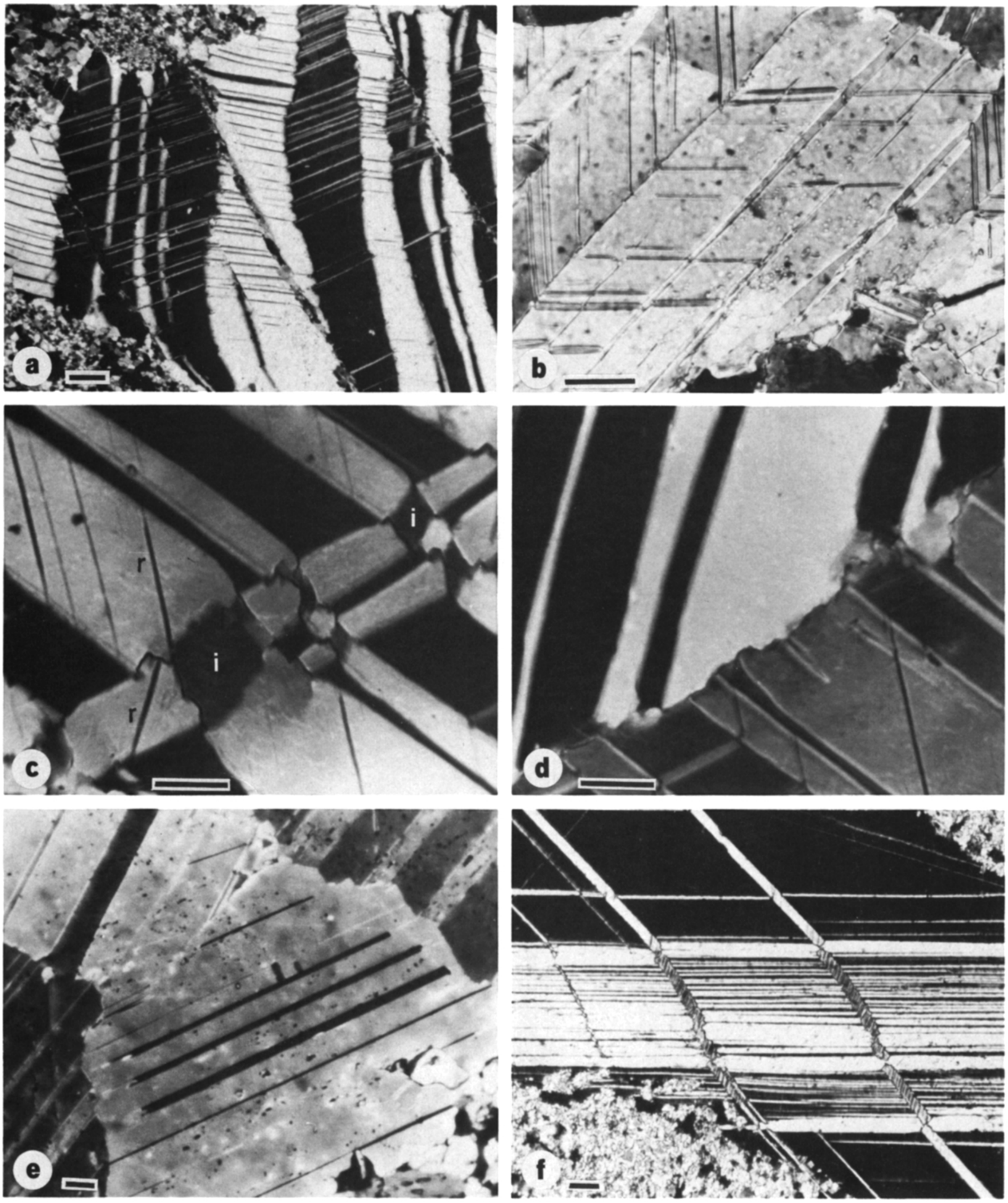


Fig. 8. Photomicrographs of ultrathin sections in crossed polars. All scale bars are 10 μm. (a) & (b) Twinned twins. Note twins meeting each other at twin boundaries. (c) Details of twin–twin intersections: r = rational (late twins); i = irrational twins. (d) & (e) Details of twin–grain boundary contacts (see discussion in text). (f) Dextral shearing by twinning, indicated by passively rotated former twin lamellae within thick twin set (horizontal).

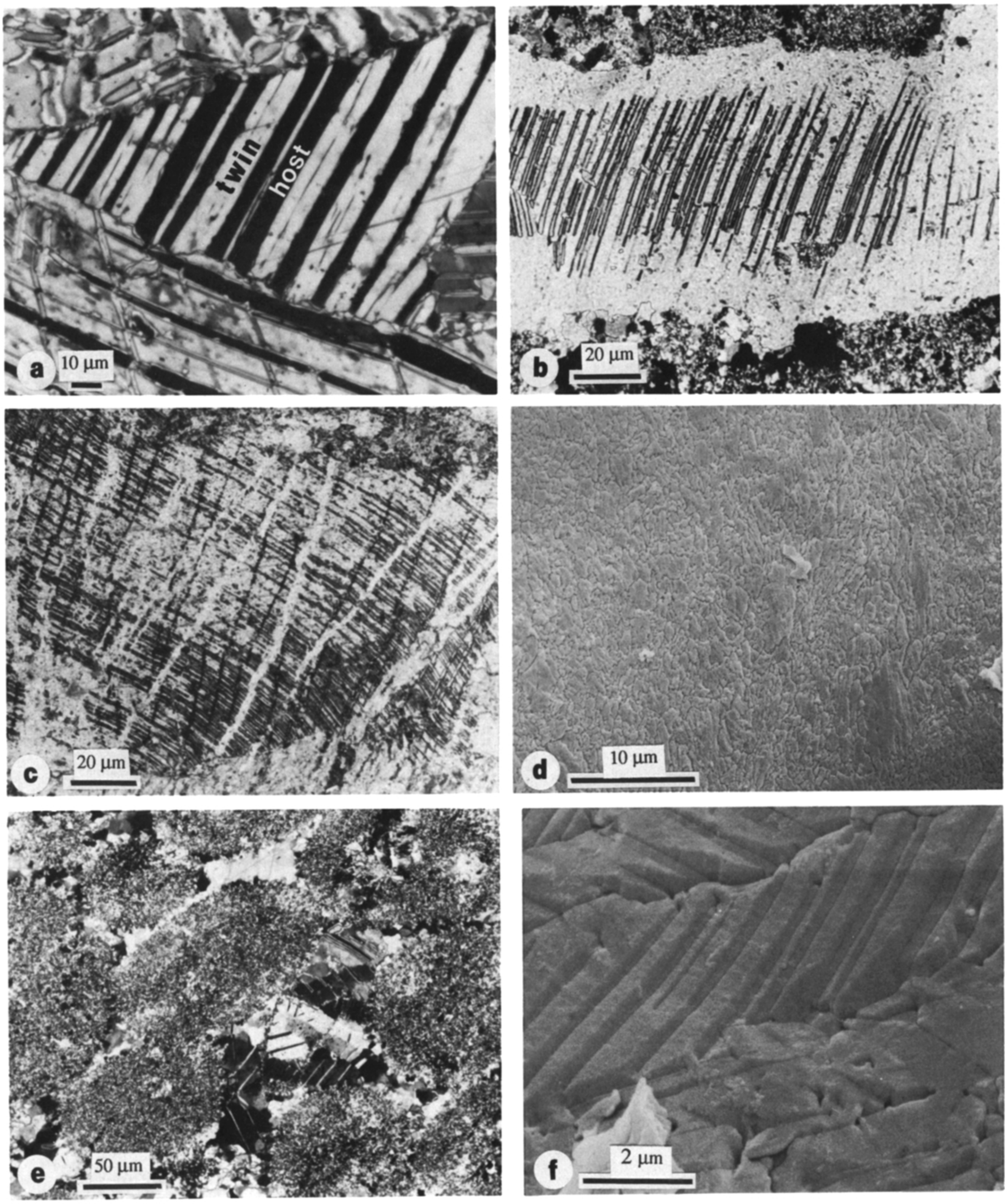


Fig. 9. Photomicrographs of twinned calcite in crossed polars. (a) Intensely twinned calcite crystal (cf. Fig. 3). (b) Central parts of an antitaxial calcite vein (horizontal) are twinned, whereas the latest vein-filling, close to the micritic wall rock, is untwinned. (c) A large, twinned calcite single crystal (crinoid stem) is crossed by microveins, filled with untwinned pure epitaxial calcite. (d) SEM picture (polished and slightly HCl-etched surface) of extremely fine-grained twinned calcite in a low-temperature mylonite (the same sample, see Figs. 10a & b). (e) Micritic pellets surrounded by a sparry, twinned matrix calcite, sample G1 (cf. Fig. 11 and Table 2). (f) SEM photomicrograph of twinned sparry matrix of sample G1.

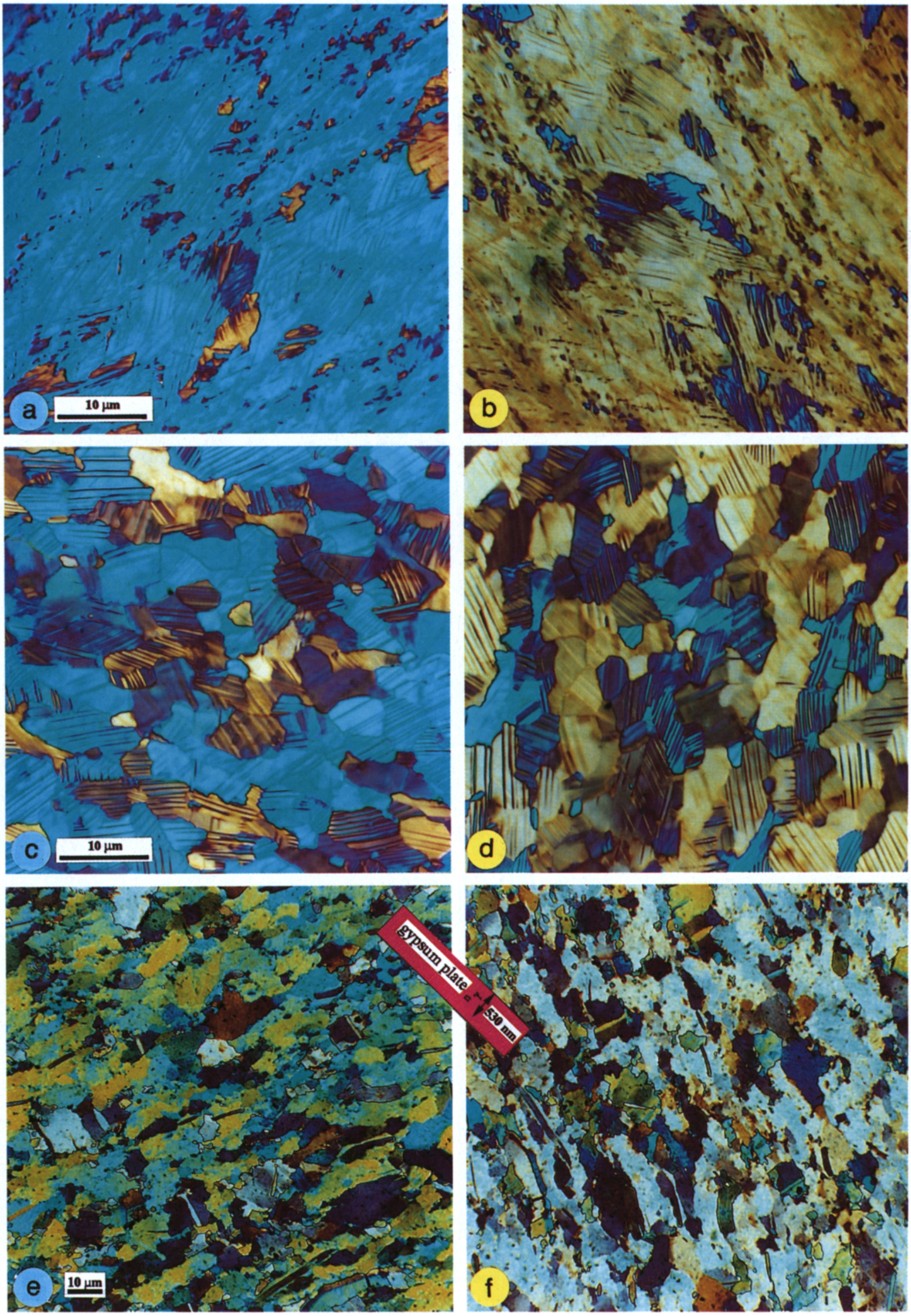


Fig. 10. Colour photomicrographs of calcite tectonites in ultrathin (<3 µm) sections (crossed polars vertical/horizontal; gypsum plate inserted). Scale bars are 10 µm. Each sample is shown in two different orientations, 90° apart, in order to illustrate the strong *c*-axis preferred orientations. (a) Fault rock from the northern Wildhorn nappe, deformed at *ca* 180°C. (b) Calc-mylonite from the Glarus thrust, deformed at *ca* 250°C. (c) Calc-mylonite from the Morcles thrust, Helvetic root zone, deformed at *ca* 330°C. This sample is slightly thicker than the two previous ones: instead of second-order blue (left row) and first-order yellow (right row), the predominant colours are second-order yellow and first-order grey, respectively.

Table 1. Comparison of the stress–strain axes and palaeopiezometer methods

Methods	*STRESS*	*STRAIN*	*axes orientations*	*relative magnitudes*	*absolute magnitudes*	*tests compatibility of twins*	*polyphased deformation*	*graphical method*	*numerical method*	*statistics*	*orientation (U-stage)*	*number of twins*	*volume of twins*	
STRESS–STRAIN AXES	**what is determined?**							**how?**			**measured items**			**comment**
Turner (1962)	x		x					x			x			**classic method**
Spang (1972)	x		x	x				x	x	x	x	x		**modified Turner, weights number of twins**
Groshong (1972)		x	x		x	x	±	x	x	x	x	x	x	**sophisticated, robust, STRAIN not STRESS!**
Laurent et al. (1981, 1990)	x		x		x	x	x		x	x	x			**very sophisticated, rigorous assumptions**
Pfiffner & Burkhard (1987)	x		x	x		x		x		x	x			**TEST of compatibility of twins, robust**
PALAEOPIEZOMETERS														**none of these test the compatibility of twins!**
Jamison & Spang (1976)	x				x					x		x		**useful, but many restrictions (uniaxial stress)**
Schmid (1982a)	x				x					x		x		**grain size dependence, experimentally**
Rowe & Rutter (1990)	x				x					x		x	x	**calibrated, but extrapolations are questionable**

strain in a rock. With the exception of Groshong (1972), however, who aimed directly at determining these small strains, most authors have correlated the small twinning strains directly with palaeostress(es). Two types of methods have to be distinguished: (1) those which determine principal strain–stress axis directions (and magnitudes) from the U-stage measurements of twins; and (2) palaeopiezometers which determine palaeodifferential-stress magnitudes only, without bothering with the orientation of stress axes. A short summary and comparison of the different methods is given in Table 1, in which the different parameters which must be measured in order to obtain certain items of information are listed. Individual methods are discussed in more detail below.

Strain (palaeostress) axis directions from twins

Turner (1953) and Weiss (1954) introduced the use of calcite twins as a 'stress' gauge. From consideration of the crystallography of calcite, Turner concluded that it must be possible to deduce geologically significant C (compression) and T (tension) directions (Fig. 1) by measuring the orientation of twin lamellae in deformed calcite rocks. Individual C and T axes are constructed from U-stage measurements of *e*-lamella and *c*-axes and then contoured on a stereographic net (Turner & Weiss 1963, pp. 242–245). Turner's (1953, 1962) method has subsequently been modified by numerous authors, either by weighting the number of twins (Spang 1972) or by facilitating the graphical interpretation of the twin data (Dietrich & Song 1984). Groshong (1972, 1974) and Groshong *et al.* (1984a) developed the weighting of twins further by measuring the relative percentage of twinned portion in each grain. This percentage is directly proportional to deformation by twinning and shear strain parameters can be calculated for each analysed grain. By means of a least squares technique, a single strain tensor (axes directions and magnitudes) can then be calculated from a large population of twins. After computation, the resulting strain tensor is compared with each twin in the set and its value is compared with the theoretically predicted one. This procedure notably permits the detection of twins of incompatible orientations, that is twins which should not have formed in the determined strain field. The percentage of these so called negative expected values (NEV) is a direct measure of the homogeneity of the twin data set. NEV may arise from inhomogeneous strain distribution in the aggregate, due for instance to the collapse of pores or stress concentrations at twin tips (see Figs. 8a & b) or around rigid inclusion grains. Some of this 'noise' in the data set can be removed by a simple 'cleaning' technique (Groshong 1972). This technique, however, will not significantly improve the results in cases where NEV are due to non-coaxial deformation, superimposed deformations and/or the passive rotation of twin lamellae in a strongly deformed aggregate.

Pfiffner & Burkhard (1987) applied the right dihedra method of Angelier & Mechler (1977) to determine graphically the maximum number of twin sets which are mutually compatible with a single compression (or tension) direction. This is a rapid test of the assumption that all twins originated from a single stress tensor. The optimum orientation (with the least NEV) of compression and tension axes as well as the type of deformation (constrictional, plane strain, oblate) are obtained graphically.

The most sophisticated stress determination methods (directions and magnitudes) to date have been developed by Laurent *et al.* (1981, 1990) and Laurent (1984). The basic assumption is a rigorously homogeneous stress distribution in the aggregate: deformation takes place on each *e*-lamella on which the shear stress component is greater than a threshold value of critical resolved shear stress τ_c) and only on these planes. In contrast with other methods, untwinned grains (and *e*-plane orientations) are taken into account as well, assuming that untwinned potential *e*-planes were in orientations for which shear stress was lower than τ_c. These methods are hampered by the time-consuming data collection and by the not-so-straightforward data processing. In principle, incompatible twin sets (NEV) are fatal in any such analysis (cf. Will & Powell 1991) and Laurent (1984) therefore proposed complicated statistical procedures to distinguish different stress tensors ('tectonic phases') rather than to discard some of the data as being noise (Groshong 1972, Groshong *et al.* 1984a). Interestingly, in their most recent papers (e.g. Laurent *et al.* 1990), Laurent and his co-workers reject up to 20% of incompatible twins rather than utilize them for the determination of superposed stress tensors.

Spectacular applications of Laurent's *et al.* (1981) and Laurent's (1984) technique are presented by Lacombe *et al.* (1990). From the orientation of up to 270 twinned and untwinned *e*-planes in a limestone specimen, three (four in one case) different stress tensors (with orientations and magnitudes of the stress axes) were calculated (Lacombe *et al.* 1990, figs. 10, 11 and 12 and table 3). Note that this makes 15 independent pieces of information on a complicated tectonic evolution, gained from one single twin data set. This procedure alone seems like stressing the data set to the yield point! Close inspection of the analyses reveals for instance that the three different stress tensors (orientations) correspond virtually to permutations of the σ_1-, σ_2- and σ_3-axes (Lacombe *et al.* 1990, station Montagney). Obviously, with three such superimposed stresses any possible orientation of a twin in a rock can be explained. More questionable still are the absolute values determined in this case: how could a subvertical compression have attained a value of 55 MPa (σ_1–σ_3) (Lacombe *et al.* 1990, table 3) in an upper Jurassic rock which was most probably never buried under more than 500 m of Cretaceous and Tertiary sediments? This maximum depth allows at most for a vertical σ_1 of around 14 MPa, barely enough to initiate twinning in a purely extensional regime (with an assumed critical resolved shear stress of 10 MPa for twinning). For more examples, in which twin strain and fault plane analyses and rock mechanics data are combined and compared to regional tectonics see the references in Lacombe & Laurent (1992).

Separation of strain tensors from twin data sets into different 'phases' has also been tried with Groshong's method (e.g. Teufel 1980, Ferrill 1991). Even if successful in cases where different 'phases' are opposed close to 90° (angle between σ_1-axes), this will always remain an ambiguous procedure. For instance, in the most extreme case, each individual twin could be explained by a minimum stress pulse with just the optimum orientation and minimum shear stress needed for twinning on this and only this orientation of twin plane. One ends up with as many phases as twins in a rock!

Twins as palaeopiezometer

Different authors have proposed using twins as palaeopiezometers (Table 1) without bothering with U-stage measurements of twin orientations. Methods are based on the crystallographic twinning law and assume a certain threshold value of the critical resolved shear stress τ_c necessary to initiate twinning. Furthermore, all methods assume a more or less rigorously homogeneous stress distribution in the aggregate. Twinning palaeopiezometry stands or falls with these assumptions. Because twinning is very dependent on stress and stress concentrations, the experimentally determined critical resolved shear stress values for twinning are generally regarded with scepticism (Cahn 1964, Tullis 1980, De Bresser 1991, p. 97ff.). From the observation of both naturally and experimentally deformed limestones, it is clear that twinning is grain-size dependent (Schmid 1982a, Rowe & Rutter 1990). This fact, however, is not easy to reconcile with the concept of a single, constant τ_c value for twinning, nor with the assumption of a homogeneous stress distribution in the aggregate! The question of homogeneous vs heterogeneous stress distribution is also a problem of scale. In the case of twinning palaeopiezometry, it is assumed that stress is homogeneously distributed on the grain scale—the aim of palaeopiezometry is to extrapolate the measured stresses to a regional, kilometric scale! In natural rocks, however, homogeneous stress distribution on the grain scale is probably a rare limiting case. The presence of pores, variations in grain size, inclusions of stronger grains (e.g. quartz) and grain boundaries not supporting shear stress are all arguments in favour of an inhomogeneous stress distribution in the aggregate (e.g. Wheeler 1991). Furthermore, twinning leads to a very heterogeneous deformation on the grain scale, steps in grain boundaries, stress concentrations at twin–twin and twin–grain boundary contacts (see illustrations in Figs. 2 and 8a & b) and therefore to an increasingly heterogeneous stress distribution with increasing strain. Often, methods are applied to fault or thrust rocks, with the aim of determining the stresses close to these faults (Jamison & Spang 1976, Rowe & Rutter 1990). Such analyses should be regarded with particular scepticism because: (1) strains are usually too large for the application of the methods (which are designed for very small strains only); and (2) within fault zones that experienced a stick–slip mechanism, twins may record peak stresses at stress concentrators during rapid slip movements or seismic shocks rather than being representative of the far-field stress of interest.

In conclusion, the ideal rock for palaeopiezometry would be a perfectly annealed, pure, evenly coarse-grained calcite marble which suffered extremely little twinning deformation at very low temperature. Bearing these fundamental restrictions in mind, the different available methods will be discussed in some detail below.

Friedman & Heard (1974) were among the first to use twins as a palaeopiezometer. They tried to calibrate the method both experimentally and with naturally-occurring twins in deep drill holes from the Texan Gulf Coast where twins originated in an extensional environment, with an inferred vertical σ_1 maximum stress component. Jamison & Spang (1976) proposed a rather simple statistical method for the determination of differential stress magnitudes (not orientations) (see also discussion by Tullis 1980). The basic assumption is a homogeneous stress distribution in the aggregate and a threshold value of critical resolved shear stress (τ_c = constant, *ca* 10 MPa for *e*-twinning, e.g. Wenk 1985, table 1). The relative number of twinned and untwinned grains in a calcite rock with randomly orientated grains can be predicted for a given stress tensor. In particular, with increasing differential stress, there will be more and more grains in which all three *e*-planes receive a sufficient component of shear stress for twinning. Consequently, the relative number of grains with no, one, two or three twins developed can be regarded as a function of differential stress magnitude. The limitations of this approach are clearly stated by Jamison & Spang (1976, p. 870), notably it assumes: homogeneous stress distribution, random orientation of *c*-axes in the aggregate, little deformation (but how little? <5%?), grain-size independence of twinning and, probably most important, the method has been calculated only for uniaxial stresses $\sigma_1 > \sigma_2 = \sigma_3$). This relatively simple method (no time-consuming U-stage measurements!) has two severe limitations. (1) Grain size is not specified and in practice one is confronted with the problem of deciding whether to count small untwinned grains or not and where to draw the line between small and large grains. (2) The mutual compatibility of twins is not verified. Once properly calibrated (grain-size dependence!) and if combined with a cross check of the mutual compatibility of twins (e.g. by Pfiffner & Burkhard's 1987 method) the method has some potential in tectonic studies, without being difficult to apply (there is no need for any computer calculations!).

The methods proposed by Laurent *et al.* (1981, 1990) rely basically on the same assumptions as the method of Jamison & Spang (1976) and share therefore the latter's limitations, but they calculate the stresses in a much more rigorous manner, notably by taking orientation data into account and thereby verifying the 'homogeneous stress' assumption. See the previous section for more details and a critique.

Schmid (1982a, fig. 5) observed in experimentally deformed limestones that twinning is dependent on both grain size and differential stress. At a given differential stress a minimum grain size seems to be required for twinning to take place (or to be optically detectable?). Accordingly it would suffice to determine the size of the smallest twinned grains in a rock to infer a maximum differential stress magnitude. Rowe & Rutter (1990) extended this method and calibrated it experimentally. This palaeopiezometer is not restricted to small strains but is more akin to the classical 'grain-size palaeopiezometers' (Twiss 1986 and references therein), notably in the tacit assumption of a steady-state microstructure. Hence many problems arise from this assumption (Schmid 1982b, p. 102). Rowe & Rutter (1990) proposed three different palaeopiezometers: (1) twinning incidence (percentage of twinned grains within a certain grain size class); (2) twin density (number of twins per mm); and (3) twin volume. All three parameters, according to their laboratory study, are directly proportional to differential stress. They seem to be independent of temperature, strain and strain rate and therefore seem to represent ideal stress gauges. Although experimentally founded, the extrapolation beyond the laboratory conditions and to nature in particular is questionable for several reasons. (1) Twinning clearly is a deformational feature and therefore the number of twins and the volume fraction of twins in the rock are basically a function of strain not stress (unless a steady state between recrystallization and deformation has been reached, which was not the case in their experiments). Therefore, using Rowe & Rutter's (1990, fig. 9) twin density palaeopiezometer will yield higher and higher differential stresses with an increasing number of twins in a rock, i.e. with increasing (non-coaxial) strain. (2) The majority of Rowe & Rutter's (1990) calibration experiments were conducted at temperatures above 400°C within an 'intracrystalline deformation' regime, that is with temperatures high enough for other slip systems (e.g. *r*- and *f*-glide) to interfere with *e*-twinning. Accordingly, their microphotographs show predominantly twins of types II and III. Natural twinning deformation at very low temperature takes place in an altogether different deformation regime (mainly type I twins) with much smaller finite strains, slower strain rates and probably an important contribution of pressure solution. For these reasons the Rowe & Rutter palaeopiezometers (twinning incidence in particular) may be most appropriate for moderately deformed anchizonal (200–300°C) limestones which show some microstructural similarities with the experiments, rather than for very low grade (0–200°C) deformation.

Twinning palaeopiezometry: summary

Several robust techniques exist for the determination of palaeostress directions and relative magnitudes (Table 1). Unfortunately, the determination of absolute magnitudes, or palaeopiezometry in the strict sense, is not as straightforward. The simplest, rapid method of Jamison & Spang (1976) may yield useful approximate values for differential stress magnitudes in very weakly deformed, coarse-grained calcite at very low temperatures—it should not be applied at higher temperatures (above *ca* 200°C), nor to strongly or multiply deformed rocks where the method is bound to overestimate stresses. The methods of Laurent *et al.* (1981, 1990) are the most complete to date, and they yield orientations and absolute values of principal stresses and seem to be capable of handling complicated polyphase deformations. These methods, however, are rather difficult and time-consuming to apply and nevertheless suffer from the same limitations as the others. They are applied only to very small deformations, in areas where strain is seemingly absent; the methods have not been calibrated in the laboratory, but efforts are being made to calibrate them with palaeodepth estimates and rock mechanics data (Lacombe & Laurent 1992). Rowe & Rutter's (1990) twinning incidence palaeopiezometer fills a gap between the very low temperature (Jamison & Spang 1976, Laurent *et al.* 1990) and the higher temperature (Schmid 1982b, Twiss 1986) 'grain size' palaeopiezometers. It seems most appropriate for rocks deformed under anchizonal conditions (200–300°C) and should not be applied to strongly deformed rocks (where it will overestimate stresses) nor to rocks which have undergone dynamic recrystallization (where it might underestimate stresses). The latter technique is the most thoroughly calibrated, however, according to Rowe & Rutter (1990). Estimated errors are at least ± 30 MPa within the range of experimental conditions—they are certainly larger for extrapolations to nature. All palaeopiezometers need better calibrations in both laboratory and field studies (Friedman & Heard 1974, Lacombe & Laurent 1992) and comparisons with present day *in situ* stress determinations.

FIELD EXAMPLES

Twinning preceding fracturing (Fig. 9c)

This sample is a coarse bio-grainstone from the northern Wildhorn nappe deformed under diagenetic conditions ($T < 200$°C). The main deformation of this specimen is transgranular to intergranular by dissolution (stylolites)–crystallization (micro veins). Both veins and stylolites clearly post-date the formation of the twin lamellae, as is illustrated in Fig. 9(c). Large single crystals (Echinoderma fragments) are first twinned and subsequently fractured. Fractures are healed with calcite which is crystallographically orientated like the host crystal but does not show twinning. Twinning strain analysis of this sample revealed strain directions which are very close to those inferred from stylolites and microveins, thus providing corroborating evidence that twinning, fracturing and dissolution took place in a similar stress field, probably during the same deformation phase. This sequence is interpreted in terms of strain hardening: after an initial ductile deformation of around 5% shortening, accommodated mainly by twinning, the material deformed predominantly by transgranular mechanisms (fracturing and dissolution–crystallization).

Very late twinning within veins (Fig. 9b)

The latest strain increments can often be determined from the vein filling of late tectonic calcite veins. Figure 9(b) shows an example of such a vein from the rear part of the Wildhorn nappe (cf. Fig. 5). Growth of large sparry calcite crystals within this vein took place by a 'crack–seal' mechanism in an antitaxial sense, i.e. with successive crack openings between the wall rock and the vein filling. Clearly the older vein filling (center of the vein) suffered from some twinning deformation whereas the latest vein filling remained undeformed. Twinning strain analyses within such veins from the Helvetic area of western Switzerland consistently have given extension axes close to the vein poles, thereby confirming their mode of formation as tensile fractures (Burkhard 1986, Burkhard & Kerrich 1988).

Twinning contemporaneous with the main deformation

This sample (G1) is an oolitic limestone from the northern Gellihorn nappe (Fig. 9e and Table 2) deformed at the limit between diagenesis and anchizonal conditions (estimated at 180°C). Pellets made of micritic ooze (mean grain size 3.0 ± 1.5 μm) are flattened and strain analyses with the R_f/ϕ–θ (Lisle 1977) or Shimamoto & Ikeda (1976) techniques for the pellet shapes are in very good agreement with those obtained by the normalized centre–centre technique (Erslev 1988). The sparry (about 0.1 mm) cement is intensely twinned with abundant thick twins (types II and III). Twin strain analysis (Spang 1972, Groshong 1972, Pfiffner & Burkhard 1987) reveals principal strain axes directions which lie very close to those obtained from the pellet shapes (Fig. 11a and Table 2). The twinning strain axes obviously record quite accurately the directions of the finite strain axes. Magnitudes of deformation by twinning, however, are only 14 and 20% (of shortening and extension, respectively) of the finite strain (Table 2). This could either signify that the sparry matrix is less deformed than the whole rock or, alternatively, that twinning accommodated only part of the intracrystalline deformation of the cement. One might expect a competence contrast between the fine-grained pellets and coarser grained cement. The close agreement between the R_f/ϕ–θ and centre–centre results testifies that no great difference in strain between matrix and markers can exist. It is obvious that twinning alone cannot lead to very large strains because of twin sets (and grain boundaries) hindering each other in their development. On the grain scale in sample G1, it can be seen that dissolution and minor recrystallization have helped to overcome such incompatibilities. Furthermore, there exists a measuring problem with twinning strain analysis: completely twinned grains and recrystallized twins are unsuitable for analysis. Thus, the largest contributors to the strain cannot be taken into account by the method which is restricted to small (less than 15% shortening) deformations. Larger twinning strains are impossible to measure but this does not mean that twinning cannot contribute to larger strains. Twinning, when more important, nevertheless leaves its traces in the deformed rock, notably by a strong crystallographic preferred orientation of the *c*-axes, which tend to form point maxima around the compression axis, that is close to the pole of the schistosity (Schmid *et al.* 1987). In the case of sample G1, a detailed texture analysis of the sparry matrix reveals some interesting aspects of texture development by twinning (Fig. 11). A stereographic representation of the twin *c*-axes shows a strong clustering around the compression axes. This is a direct consequence of the twinning law (Fig. 1). If twinning went to completion within many of these already twinned grains, this would obviously lead to a pronounced *c*-axis point maximum.

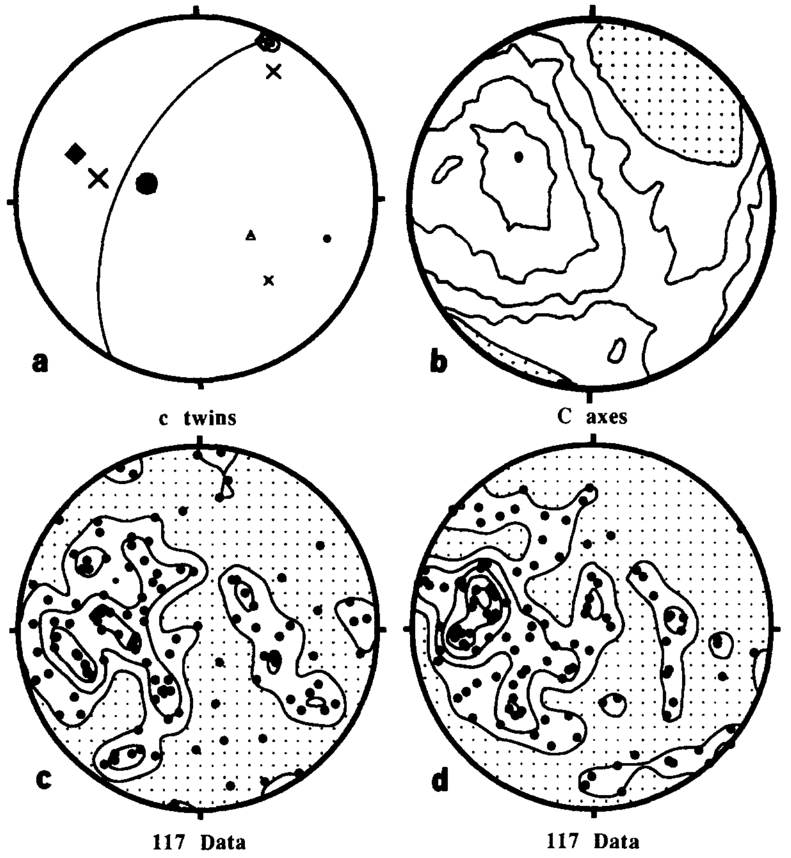


Fig. 11. (a) Equal-area projections of strain axes determined with different methods (× = Spang, diamonds = Groshong, ○ = finite strain from pellet shape; cf. Table 2). Open symbols = extension axes, filled symbols = compression axes, small symbols = intermediate axes. (b) Compression diagram (right dihedra method, Pfiffner & Burkhard 1987), contours corresponding to 30, 50, 60, 70 and 80% compatible twin sets. Eighty-nine out of 117 twins are mutually compatible, giving 24% NEV (black spot). (c) *c*-axes of twins only are plotted and contoured at 1, 2 and 3 times uniform. (d) Compression axes (C-axes of Turner's method) are contoured at 1, 2, 3 and 4 times uniform.

Table 2. Sample G1 strain parameters (see Fig. 11)

3-D Results	e_1	e_2	e_3	X	Y	Z	NEV
TWINNING STRAIN							
Spang (1972)	0.27	0.028	-0.3	33/20	140/40	282/44	
Groshong (1972)	0.094	-0.029	-.065	24/06	125/60	291/30	26%
Pfiffner & Burkhard (1987)				30/10	127/38	290/52	24%
FINITE STRAIN (pellets)	0.64	-0.12	-0.3	27/05	119/24	287/66	
2-D Results	face 1		face 2		face 3		
Pellets (finite strain)	R_s	Φ	R_s	Φ	R_s	Φ	
Polargraph, Elliott (1970)	1.93	117°	1.29	78°	1.49	109°	
$R_f/\Phi-\theta$, Lisle (1976)	1.92	117°	1.28	77°	1.45	108°	
Shimamoto &Ikeda (1976)	1.92	117°	1.29	77°	1.46	110°	
Centre-Centre, Erslev (1988)	1.9	120°	1.3	78°	1.5	110°	

Twinning as the main contributor to strong c*-axis maxima in calcite tectonites* (Fig. 10)

Three extremely deformed fault and thrust rocks have been chosen to illustrate the importance of twinning as a deformation mechanism in highly strained limestone tectonites. Deformation temperatures are estimated from the regional geology and stable isotope thermometry (quartz–calcite) at 180, 250 and 330°C, respectively (Burkhard & Kerrich 1988). All three mylonites have extremely strong *c*-axis preferred orientations (easily visualized by the use of a gypsum plate as shown in Fig. 10). Twinning is thought to be responsible for this strong lattice preferred orientation, although twins are not a major microstructural feature in all of these rocks.

In the first sample (Figs. 10a & b), a low-temperature fault rock from the Wildhorn nappe, thin twins are visible in larger grains but many of the grains are less than *ca* 2 μm in diameter which makes it difficult to detect any microstructural details by optical microscopy. The use of a gypsum plate reveals an extremely strong *c*-axis, preferred orientation which probably stems from intense twinning deformation. Twins in extremely small grains are visible in SEM pictures as preferentially etched straight tiny grooves (Fig. 9d). According to the Rowe & Rutter (1990) twinning incidence–grain size palaeopiezometer, the presence of twins within grains below 2 μm diameter would indicate differential stresses in excess of 400 MPa, a value which can hardly be interpreted as the relevant regional 'far field' stress.

In the second sample (Figs. 10c & d), a mylonite sample from the famous Glarus thrust, twins are omnipresent even in grains of 5 μm and less in size. Again, the presence of twins in almost every grain, despite a grain size of less than 5 μm, would indicate extremely high differential stresses (>200 MPa) using the Rowe & Rutter (1990) palaeopiezometer. High differential stresses (up to 320 MPa) have previously been reported for these mylonites by Briegel & Goetze (1978) and Pfiffner (1982, table 2) based on the dislocation density and grain size, respectively. Note, however, that the same mylonite has also been interpreted as a natural example of superplastic deformation (Schmid *et al.* 1977, Schmid 1982a). Very low yield strength within the mylonites, characteristic of superplasticity, was thought to be a key factor for the extreme strain localization (>35 km of overthrust within a shear zone of a few metres width only). The assumption of superplastic deformation within the thrust zone was thought to explain the 'paradox of large overthrusts' (Hsü 1969, Schmid 1975, Price 1988). The microstructures within the calc-mylonite, notably a strong *c*-axis preferred orientation and abundant twins, however, seem hardly compatible with a superplastic deformation regime (see Figs. 10c & d). The question arises if the observable (micro-) structures and the inferred high differential stresses are at all related to the main thrusting event. They could represent late, insignificant deformations along the thrust plane.

In the third sample (Figs. 10d & e), a calc-mylonite from the inverted limb of the Morcles nappe, fairly thick twins are frequent. These twins have smooth boundaries and a rather constant thickness toward the grain boundaries, indicating that twinning and grain boundary migration were acting simultaneously. These twins are neither late, post-tectonic nor early pre-metamorphic features.

It is noteworthy that all the twins within these highly deformed samples occur mainly as single sets. Twinning was certainly not the only deformation mechanism in these tectonites, which were deformed probably by a combination of twinning plus *r*- and/or *f*-glide and maybe grain boundary sliding. Furthermore, all three samples show evidence for dynamic recrystallization. Recrystallized grains are extremely small (<1 μm) in the low-temperature sample (Figs. 10a & b), whereas the microstructure of the highest temperature sample (Figs. 10e & f) (T = 330°C) is dominated by grain-boundary migration and a much larger grain size. Twinning palaeopiezometry in these rocks yields extremely high differential stresses which are difficult to accept as geologically significant.

CONCLUSIONS

Twins are widespread deformational features in calcite of any provenance. Twinning is an exceptional case of an intracrystalline deformation mechanism in several regards. The critical resolved shear stress for twinning is very low (about 10 MPa) and much less temperature sensitive than for other glide systems. Twinning deformation is thus possible at ambient temperatures, under virtually no cover and at very low differential stresses. Twins are very easily detected in thin sections, even if deformation is less than 1%. The twinning law, that is the crystallographic orientation of the shear plane and a unique shear sense are well known: twins are perfect intracrystalline simple shear zones. These characteristics make twins ideal stress–strain markers for weakly deformed rocks, and several robust methods are available for the determination of the orientations of principal stress–strain axes and strain magnitudes (Table 1). Twinning palaeopiezometers, however, are to be regarded with some scepticism despite many efforts at perfecting both numerical calculations (e.g. Laurent *et al.* 1981, 1990) and experimental calibration (Rowe & Rutter 1990).

Different types of twin are easily distinguished in thin section using simple geometric criteria (Fig. 6). Twin types can be mapped and used as approximate indicators of deformation temperature as exemplified in the case of the western Helvetic nappes (Fig. 5) or the French Chaînes Subalpines (Ferrill 1991). The development of thick twins (type II) rather than an increasing number of thin (type I) twins corresponds to a temperature of around 150°C. The (thermodynamic?) reason for this is not well understood. Type III, curved twins and twins in twins are frequently observed within the anchizone (*ca* 200–300°C). The development of these can be related to the onset of intracrystalline deformation mechanisms other than *e*-twinning, particularly *r*- and *f*-glide, both known to be strongly temperature dependent (De Bresser 1991). Type IV, recrystallized twins (migrated twin boundaries) are frequently observed at temperatures above *ca* 250°C and are very sensitive indicators of syntectonic, dynamic recrystallization.

Twinning is a very important deformation mechanism at least up to middle greenschist facies, for which conditions it is a main contributor to the development of strong *c*-axis preferred orientations in limestone tectonites. Detailed observations of twins have helped to elucidate details of microstructural interest such as the establishment of the deformation history or the identification of intracrystalline deformation mechanisms.

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