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NATURE AND DYNAMIC INTERPRETATION OF DEFORMATION LAMELLAE IN CALCITE OF THREE MARBLES

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ABSTRACT. The fabrics of three crystalline marbles lacking obvious effects of post-crystalline granulation are described in detail. Particular attention is paid to $\{01\bar{1}2\}$ lamellae optically recognizable as twins. These have restricted ranges of orientation from which it is possible to deduce simple systems of applied stress that could account for observed twinning. The procedure followed in developing this dynamic interpretation of twin lamellae is described. The orientation of *c* axes and that of visible $\{01\bar{1}2\}$ lamellae in grains lacking recognizable twinning can also be explained in terms of the same system of applied stress in any given case. It is concluded that preferred orientation patterns of *c* axes of calcite were determined during the main phase of metamorphism; but visible $\{01\bar{1}2\}$ lamellae reflect a very late phase of incipient deformation. The above dynamic interpretation of natural marble fabric is based on experimental data and on fabrics observed in experimentally deformed marbles.

Most visible lamellae in the three specimens described are parallel to $\{01\bar{1}2\}$. A few are partings parallel to $\{10\bar{1}1\}$. No other types of lamellae were recorded.

THE PROBLEM

IN most marbles some grains of calcite show lamellar twinning on $\{01\bar{1}2\}$, recognizable by differences in optical behavior (notably extinction) between lamellae and host crystal. Examination of a marble section with a universal stage reveals the existence of many other sharply defined lamellae of linear thickness which cannot be identified by optical means as twins. These may possibly be twin lamellae of ultramicroscopic thinness; or they may perhaps be deformation lamellae or partings of another kind. The great majority of such lamellae are strictly parallel to $\{01\bar{1}2\}$.

Similar $\{01\bar{1}2\}$ lamellae, in some cases demonstrably twinned, are abundantly developed during laboratory deformation of marble, dry or in the presence of water, at confining pressures of 5,000 to 10,000 atmospheres, and at temperatures ranging from 20° to 300° C. Associated with these in particular cases are lamellae $\{02\bar{2}1\}$, partings $\{10\bar{1}1\}$ and irrationally situated lamellae of other orientations. The nature and significance of the various types of lamellae in artificially deformed marbles is discussed in a paper by Mrs. I. Borg and the writer, now in the press.

The problem raised in the present paper concerns identity and dynamic interpretation of lamellae in calcite of marble in general, in the light of what has been determined in the fabrics of experimentally deformed marbles. For this purpose three calcite marbles have been selected. All are coarsely crystalline and are composed of clear grains with sharply defined boundaries, lacking the marginal granulation, local strain and cloudiness that are so conspicuous in many artificially deformed marble specimens. Their general microscopic appearance suggests that metamorphic deformation has been outlasted by crystallization. In other words the present grain outlines, and presumably the space-lattice orientation pattern of the fabric, appear to have developed under conditions favoring recrystallization; and the crystallization process seems to have continued until and possibly after, the main phase of deformation had ceased. Yet there are sharply defined $\{01\bar{1}2\}$ lamellae in many such grains. These, however obvious they may be on rapid inspection of the section, would seem to be trivial features of the fabric due to minor deformation subsequent to crystallization of the marble. Is there additional evidence supporting this view? If so, are the visible lamellae due to some simple system of imposed stress, or did they form in response to random stresses set up during post-metamorphic cooling and unloading? What is the role of twin-gliding in development of visible lamellae? Are lamellae other than those parallel to $\{01\bar{1}2\}$ present in natural marble fabrics?

One object of this paper is to attempt to answer such questions in the light of experience gained from study of experimentally deformed fabrics. Another is to supply detailed descriptions of natural marble fabrics for general comparison with fabrics of experimentally deformed marbles. Rocks in which post-crystalline deformation seems to have been slight have been selected so as to simplify the problem as much as possible.

BANDED MARBLE, MORAY FIRTH, SCOTLAND

Occurrence and general features of fabric

The specimen, 58M53, is a marble known as the "Boyne limestone" collected at Boyne Bay on the southern shore of Moray Firth in eastern Scotland. It is associated with sedimentary schists which have been metamorphosed at high temperatures and have been folded without strong internal deformation; but within a few hundred yards of this particular locality the whole metamorphic series has undergone intense local deformation along a major zone of dislocation known as the "Boyne line."

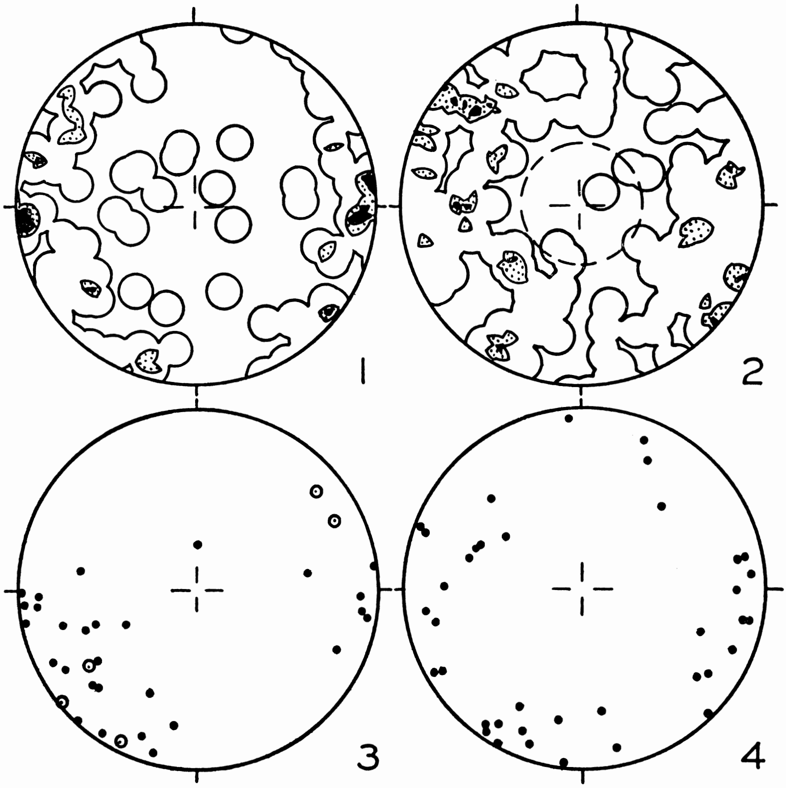
A prominent bedding foliation, S_1 is marked by alternation of bluish micaceous laminae less than 1 mm. thick, and bands 3 mm. to 7 mm. thick composed almost entirely of calcite. The calcite occurs in nearly equant clearcut grains averaging 0.1 to 0.2 mm. in diameter. Many intergranular boundaries are almost straight as seen in sections normal to the schistosity. Most grains show widely spaced sharp lamellae, typically two sets per grain. Individual lamellae in one grain occasionally match corresponding lamellae of closely similar orientation in adjoining grains, and so strengthen the general impression that lamellae are structures of late origin. The diagnostic angle of $26° \pm 2$ between the plotted poles of lamellae and the corresponding *c* axes identifies the great majority of lamellae as being parallel to $\{01\bar{1}2\}$. The only exceptions are rare instances of continuous sharp partings parallel to $\{10\bar{1}1\}$, which closely resemble $\{01\bar{1}2\}$ lamellae in general appearance, and seem to differ from the common discontinuous rather inconspicuous $\{10\bar{1}1\}$ cleavages present in many grains.

Preferred orientation of calcite

Orientation of c *axes and* $\{01\bar{1}2\}$ *lamellae.*—Figure 1 shows the preferred orientation pattern of *c* axes measured in 75 grains. The degree of preferred orientation is relatively slight. The only consistent feature is a tendency for the *c* axes to intersect the foliation at angles greater than 45°, rather than less than 45°. Within the sector of concentration there is a distinct maximum for axes perpendicular to the foliation.

Figure 2 gives the orientation of 130 prominent sets of $\{01\bar{1}2\}$ lamellae measured in 75 grains. Preferred orientation is by no means strong, especially if allowance is made for existence of a central "blind spot" (inner circle of figure 2) due to inaccessibility of lamellae lying nearly parallel to the section. However it is clear that lamellae on the whole tend to be inclined at angles of less than 50° to the foliation.

Petrofabric analysis of marble from Yule Creek, Colorado, that has been deformed in the laboratory (e.g., Turner and



Figs. 1-4. Boyne marble, 58M53. Orientation of calcite grains. Foliation, S_1, normal to plane of projection, trends vertically.

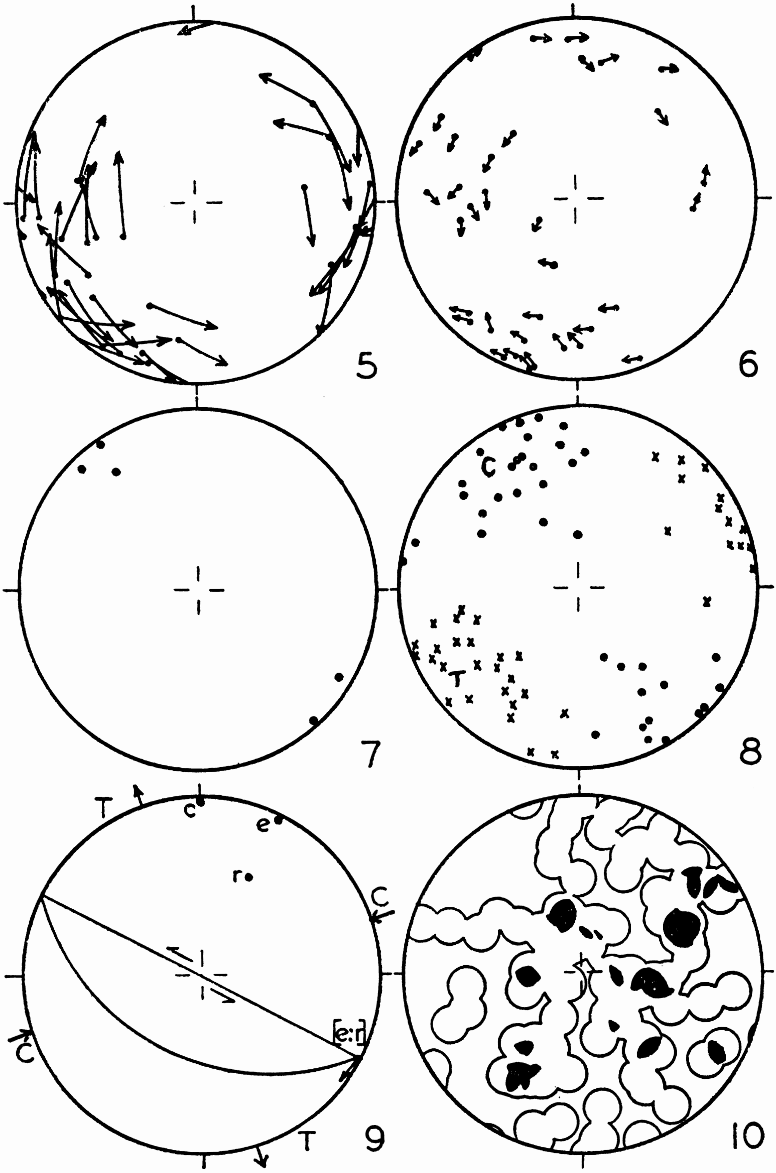
Fig. 1. *c* axes in 75 grains. Contours at 5%, 4%, 1%, per 1% area.

Fig. 2. Poles of prominent $\{01\bar{1}2\}$ lamellae (130 in 75 grains). Contours at 6%, 3%, 0.8%, per 1% area.

Fig. 3. *c* axes in 33 grains with $\{01\bar{1}2\}$ twins. Circled dots represent grains with two sets of twins.

Fig. 4. Poles of 38 $\{01\bar{1}2\}$ twin lamellae (in 33 grains).

Ch'ih, 1951, p. 902) has shown that where the strain is of the order of 10% to 25% elongation or shortening, the edge [*e*:*e*′] between the two best developed sets of $\{01\bar{1}2\}$ lamellae per grain develops strong preferred orientation. In the present rock no such orientation can be observed. The pattern of [*e*:*e*′] edges shown in figure 10 can be explained entirely by the existence of a belt of minimum concentration of *c* axes (fig. 1) necessitating a corresponding belt of concentration of [*e*:*e*′]



edges (the angle between *c* and [*e*:*e*′] in any crystal is about 76°). Lack of significant orientation in figure 10 is only to be expected on the basis of our original assumption that in the Boyne marble visible {01$\bar{1}$2} lamellae are products of a late comparatively trivial deformation.

Orientation phenomena in twinned crystals.—In about 30 per cent of the measured sets of {01$\bar{1}$2} lamellae, twinning can be recognized optically in one or more individuals. The crystals in question—henceforth designated "twinned crystals"—have been considered separately from crystals which lack recognizable twinning of {01$\bar{1}$2} lamellae.

Comparison of figures 3 and 1 demonstrates the sharply restricted range of orientation of *c* axes of twinned crystals. A similarly restricted orientation of twin lamellae (fig. 4) is equally obvious. It would seem likely that twinning has occurred in response to some uniform simple stress that has been imposed upon an aggregate of calcite grains already having the state of preferred orientation of lattice illustrated by figure 1. Those grains suitably oriented in relation to the applied stress have twinned; in other grains obviously twinned lamellae have failed to appear. Three independent lines of evidence collectively lend strong support to this hypothesis:

(1) Figure 5 demonstrates a regular relation in space between *c* axes of similar orientation and twinned {01$\bar{1}$2} lamellae in the same grains. For each grain an arc has been drawn from the *c* axis pole to the pole of the {01$\bar{1}$2} twin lamella. The general direction of departure of arcs from any group of mutually adjacent *c* axes is remarkably uniform.

2) The glide lines—edges (01$\bar{1}$2):(10$\bar{1}$1), henceforth designated [*e*:*r*]— for twin gliding in observed twin lamellae show a high degree of preferred orientation (fig. 6). Moreover the

Figs. 5-10. Boyne marble, 58M53. Orientation of calcite grains. Foliation, S_1, normal to plane of projection, trends vertically (except in fig. 9).

Fig. 5. *c* axes (dots) and poles of {01$\bar{1}$2} twin lamellae (arrow heads) in 27 typical twinned grains. [To avoid confusion from nearly coincident arcs, 6 grains shown in figure 3 have been omitted].

Fig. 6. Glide lines (01$\bar{1}$2):(10$\bar{1}$1) in twinned grains of figures 3-5. The arrow is drawn toward the *c* axis in the acute angle of intersection between *c* and the normal to {01$\bar{1}$2}.

Fig. 7. Bisectors of acute angles between glide lines (01$\bar{1}$2):(10$\bar{1}$1) in 5 grains with two sets of twins each.

Fig. 8. Axes of compression (dots) and tension (crosses) most favoring observed twinning on {01$\bar{1}$2} in individual grains.

Fig. 9. Graphic construction for determining respective axes of tension (T) and compression (C) most favoring twin gliding (in sense of arrows) on a plane (01$\bar{1}$2) = *e*. Poles of (01$\bar{1}$1) = *r*, *c* axis, and edge (01$\bar{1}$2):(10$\bar{1}$1) = [*e*:*r*] are also shown.

Fig. 10. Edges [*e*:*e*′] between prominent {0112} lamellae (twinned or otherwise; 87 in 75 grains). Contours at 3.5%, 1%, per 1% area.

sense as well as the direction of glide lines is generally uniform. This is brought out in figure 6 by drawing from the point representing each glide line an arrow pointing toward the corresponding *c* axis across the acute angle of intersection between *c* and [*e:r*]. For this and other details of graphic construction the reader is referred to figure 9. (To construct the glide line [*e:r*], align the respective poles of *c* and of the twin lamella *e* upon a great circle of the net; then [*e:r*] lies on this great circle at an angular distance of 90° from the pole of *e*.)

(3) The applied stresses that could be most effective in causing twin gliding in a particular $\{01\bar{1}2\}$ lamella lie in the plane containing *c* and the normal to the lamella in question, and are inclined at 45° to the latter (Handin and Griggs, 1951, pp. 866-869, fig. 3). They are respectively: (a) a tension (T in figure 9) applied at an angle of 19° to *c*, measured in the opposite direction to the arc *ce*; or (b) a compression (C in figure 9) applied at 71° to *c*, measured in the same direction as the arc *ce*. The directions T and C have been determined for each case of twinning recorded in the present specimen, and have been plotted to give figure 8. The grouping of both types of direction is strikingly regular. Figure 8 shows that a tensile force applied in the vicinity of T or a compression applied at C, or both forces acting together, could account for all twinning observed in the measured grains. The same forces could also explain absence of recognizable twins in the remaining majority of grains. Note that the arrows of figure 6 must, by the nature of the graphic construction employed (fig. 9), point toward the direction of applied tension and away from that of applied compression.

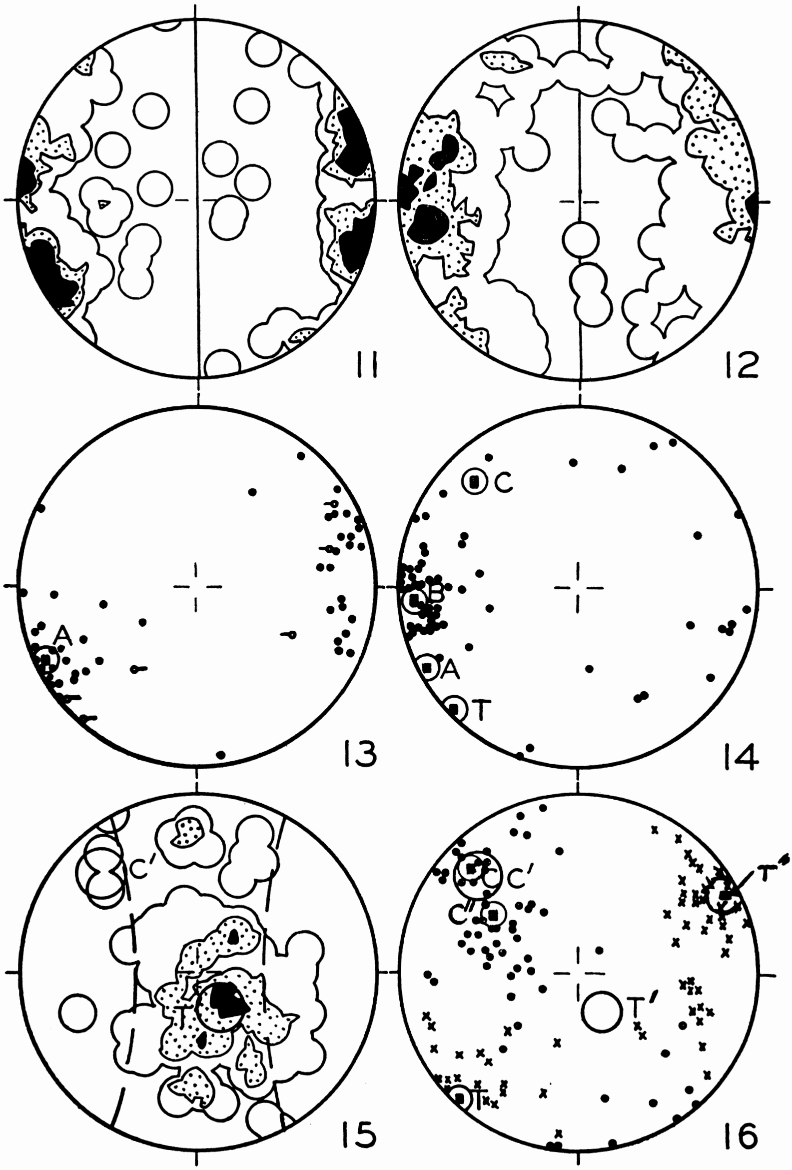
If a tensile force is applied subparallel to the *c* axis of a calcite crystal, the resolved shear stress coefficient in the direction and sense favoring twin gliding may simultaneously be high on all three $\{01\bar{1}2\}$ planes of the lattice. But if compression is applied so as to induce a high resolved shear stress for the direction of twin gliding on one $\{01\bar{1}2\}$ plane, that for the other two $\{01\bar{1}2\}$ planes of the same lattice must necessarily be low (Handin and Griggs, 1951, fig. 3). Consequently we might expect to find many grains with two, and some with three, sets of twin lamellae in a marble fabric deformed under simple tension; but simple compression should give a fabric in which most twinned grains have only one set of twin lamellae, only a few have two, and none have three. This second condition corresponds to what has been observed in the Boyne marble 58M53. Only five out of 38 twinned grains show two sets of twins. Moreover if the bisector of the acute angle between the two glide lines is plotted for each of these five grains (fig. 7), it is found consistently to approximate closely the mean direction of applied compression obtained from figure 8.

YULE MARBLE, COLORADO

In an earlier account of the fabric of marble from Yule Creek, Colorado (Turner, 1949, pp. 611-612), attention was drawn to the restricted range of orientation of twin lamellae $\{01\bar{1}2\}$ and of *c* axes of grains showing definite twinning. This matter is discussed further below in the light of a more detailed examination of a single section of Yule marble (no. 158) cut perpendicular to the foliation. Results of this analysis are strikingly similar to those recorded for the Boyne marble. They are illustrated by figures 11 to 16 and may be summarized as follows:

(1) Orientation diagrams for 100 *c* axes and for 218 prominent $\{01\bar{1}2\}$ lamellae in the same grains are reproduced as figures 11 and 12. The general concentration of *c* axes and of $\{01\bar{1}2\}$ poles around the pole of the foliation is typical of the Yule marble fabric as previously recorded (cf. Turner and Ch'ih, 1951, p. 892). This restricted range of lattice orientation restricts the range of possible orientation of $\{01\bar{1}2\}$ twins within the fabric rather more than was the case with the Boyne marble.

(2) In most grains two sets of $\{01\bar{1}2\}$ lamellae are well developed and the third is weak or absent. The edge $[e{:}e']$ between two well-developed sets of lamellae per grain are necessarily concentrated between the broken arcs of figure 15 on account of the strongly preferred orientation of the grain lattices. But within this belt there is strong concentration of edges around the point T′. By analogy with similar patterns recorded for artificially deformed marble (Griggs, Turner, Borg and Sosoka, 1951, fig. 10, p. 1400), that of figure 15 could result from either tension applied in the vicinity of T′ or compression near C′.



(3) In this particular section of Yule marble definite twinning on {01$\bar{1}$2} lamellae is commoner than in most other specimens of the same rock. Some degree of recognizable twinning was recorded for 60 sets of lamellae in 54 grains. The *c* axes

of such grains are shown in figure 13, and the poles of twin lamellae in figure 14. The ranges of orientation are much more restricted than those of figures 11 and 12, respectively.

(4) From the centers of concentration of *c* axes (A) and twin lamella poles (B) for recognizably twinned grains, the respective directions of compression (C) and tension (T) that could account for twinning have been constructed graphically and plotted in figure 14. Similar compression and tension axes have been determined individually for each twinned grain (figure 16). These points are strikingly grouped around centers respectively designated C″ and T″. On the same diagram C and T of figure 14 and C′ and T′ of figure 15 have also been plotted for comparison. The close approximation of C, C′ and C″ is striking. On the other hand T′ (deduced from orientation of edges [*e*:*e*′] is far removed from T and T″. Orientation of twin lamellae and *c* axes of grains in which they occur can thus be explained satisfactorily by assuming a late compression applied in the vicinity of C′, or a tension applied near T. But only the compression can explain the orientation of [*e*:*e*′] edges as determined for all prominent $\{01\bar{1}2\}$ lamellae (twinned and otherwise).

Figs. 11-16. Yule marble (No. 158; not experimentally deformed). Orientation of calcite. Foliation is normal to plane of projection and trends vertically.

Fig. 11. *c* axes in 100 grains. Contours at 5%, 3%, 1%, per 1% area.

Fig. 12. Poles of prominent $\{01\bar{1}2\}$ lamellae (218 in 100 grains). Contours at 4%, 2.5%, 0.5%, per 1% area.

Fig. 13. *c* axes of 54 grains (out of 100) with $\{01\bar{1}2\}$ twins. Points with horizontal bar represent grains with two sets of twin lamellae. A = center of concentration of *c* axes.

Fig. 14. Poles of 60 $\{01\bar{1}2\}$ twin lamellae (in 54 out of 100 grains). A = center of concentration of *c* axes (fig. 13); B = center of concentration of lamella poles; C and T are respective axes of compression and tension constructed from A and B.

Fig. 15. Edges [*e*:*e*′] between prominent $\{01\bar{1}2\}$ lamellae (twinned or otherwise; 105 in 100 grains). T′ and C′ are respective axes of tension and compression that could account for the orientation of [*e*:*e*′].

Fig. 16. Axes of compression (dots) and tension (crosses) most favoring observed twinning on $\{01\bar{1}2\}$ in individual grains. C and T as in figure 14; C′ and T′ as in figure 15; C″ and T″ are respective centers of concentration of individual compression axes (dots) and tension axes (crosses).

(5) Finally the glide lines determined for individual {01$\bar{1}$2} twin lamellae are plotted in figure 17. Because of the strong preferred orientation of *c* axes (figure 11), edges of the [*e*:*e*′] type must be concentrated within the belt bounded by the arcs LL and MM (since such edges intersect the *c* axis at 64°). The glide lines of figure 17 are concentrated within a sector of this belt such that they also make angles of between 30° and 60° with the axis of assumed compression C″ of figure 16. Note how both the direction of applied stress and the initial state of orientation of the grain lattices determine the pattern of the glide-line diagram.

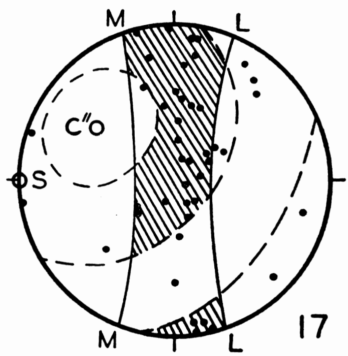


Fig. 17. Calcite of Yule marble (No. 158). Orientation of projection, as in figures 11-16. Glide lines (01$\bar{1}$2):(10$\bar{1}$1) in twinned grains of figures 13, 14. C″ is the center of compression as in figure 16. Broken arcs represent small circles about C″ at angular distances of 30° and 60°. Full arcs LL, MM represent a small circle about S (pole of foliation) at 70° from S. The overlapping area is shaded.

FOLIATED MARBLE, SONORA, CALIFORNIA

Field data

The specimen (55M50) was collected from a thin bed of marble interstratified with low grade schists which outcrop on California state highway 108 immediately east of the town of Sonora. These rocks form part of the "bed-rock series" of the Sierra Nevada western foothills region, and trend approximately parallel to a contact with intrusive granodiorite not far east of the outcrops under consideration (Heyl and Wiese, 1949). Foliation, parallel to bedding, is vertical and strikes N20°W. A prominent lineation in the schists, due to intersection of surfaces of strain-slip with the principal foliation, plunges S20°E at 45°. No corresponding lineation is seen in the marble; and foliation, too, is less conspicuous than in the schists.

General character of marble fabric

Examination of an oriented specimen (with several faces roughly polished) and of three mutually perpendicular oriented micro-sections reveals the following elements in the marble fabric (fig. 18):

S_1 = bedding and foliation; strike N20°W, dip vertical; marked by rough fissility of the specimen and by alternation of coarse white and very thin fine-grained gray bands.

S_2 = roughly parallel slip surfaces slightly displacing S_1; marked microscopically by parallel alignment of elongated grains in local bands a fraction of a millimeter thick. Strike S45°E; dip 70° to SW (determined by plotting on a projection net the traces of S_2 on variously oriented sections).

L_1 = irregular lineation, due to slight small-scale undulation of S_1.

J_1 = joints striking N70°E, dipping 38° to SSE.

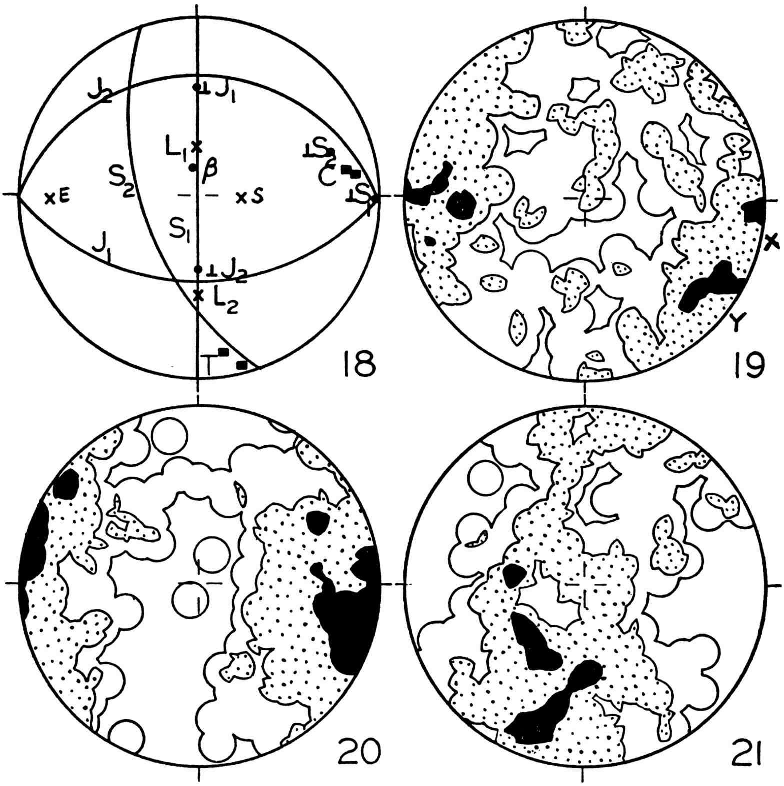
J_2 = joints striking N70°E, dipping 58° to NNW.

Under the microscope the rock is seen to be composed mainly of calcite grains 0.5 mm. to 1 mm. in length with distinct elongation parallel to the trace of S_2 or in some cases S_1. Parallel to S_1 are bands less than 0.5 mm. thick composed of much smaller grains of calcite, plentiful small crystals of apatite, and less abundant grains of sphene, micas, albite and pyrite. These bands are assumed to represent relict bedding. Twinning on $\{01\bar{1}2\}$ is conspicuous in much of the coarse calcite.

Investigation of preferred orientation of calcite was confined to the dominant coarse material. Two mutually perpendicular sections, both cut normal to the foliation S_1, were used—the one oriented normal to the strike of S_1, the other being geographically horizontal. Plotted points representing measurements made on the second of these sections were rotated on the projection net into the plane of the first section. All fabric diagrams therefore are drawn on the plane normal to the strike of S_1, looking towards S20°E.

Preferred orientation of calcite lattice

Orientation of c *axis.*—The optic axis was measured in each of 300 grains—150 grains in each section. Though {01$\bar{1}$2}



Figs. 18-21. Sonora marble, 55M50. Megascopic fabric and orientation of calcite. All diagrams are projected on plane normal to strike of foliation S_1, looking S20°E.

Fig. 18. Foliation S_1, *s*-surfaces S_2, joints J_1, joints J_2, lineation L_1 (in marble), lineation L_2 (in adjacent phyllites). The axis β is transferred from figure 27. S = south; E = east.

Fig. 19. *c* axes of calcite (307 grains measured in two mutually perpendicular sections). Contours at 3%, 1%, 0.3%, per 1% area.

Fig. 20. Poles of most prominent {01$\bar{1}$2} lamellae (1 per grain in 307 grains). Contours at 3%, 1%, 0.3%, per 1% area.

Fig. 21. Edges [*e*:*e*′] between prominent {01$\bar{1}$2} lamellae (291 in 307 grains). Contours at 3%, 1%, 0.3%, per 1% area.

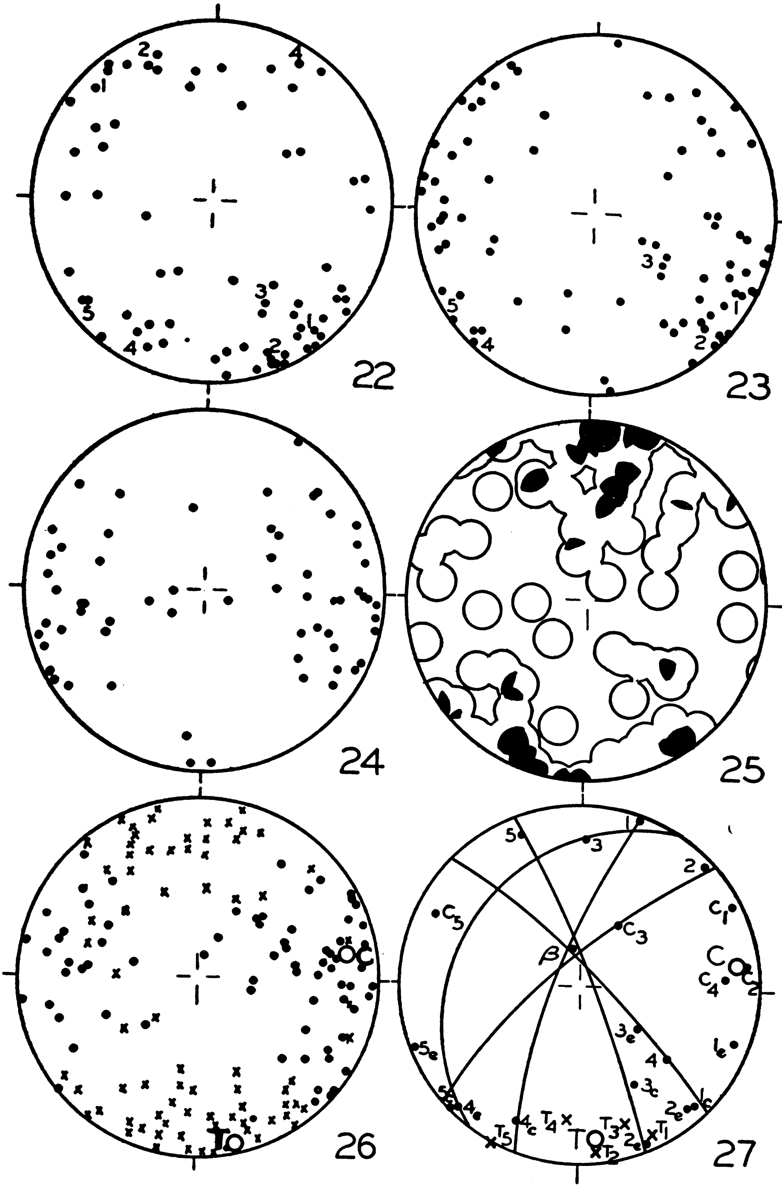
twinning is conspicuous in many grains there is seldom any doubt as to which of the alternative positions of the *c* axis represents the dominant space lattice of any grain. Figure 19 is a collective orientation diagram for *c* axes of 307 grains. The pattern of preferred orientation is weak, but shows three features all of which are obvious in both of the partial diagrams upon which figure 19 is based: (1) a broad area of concentration XY asymmetrically inclined to S_1; (2) within this, a small maximum coinciding with the pole of S_1; (3) an ill-defined zone of minimum concentration of axes parallel to S_1.

Orientation of $\{01\bar{1}2\}$ *lamellae.*—Figure 20 shows preferred orientation of poles of most conspicuous $\{01\bar{1}2\}$ lamellae—309 sets measured in 300 grains. The only persistent feature of the diagram is a broad zone of concentration eccentrically situated with reference to the poles of S_1 and S_2 and overlapping the broad *c*-axis maximum of figure 19.

Orientation of edges $[e{:}e']$.—Preferred orientation of the edge $[e{:}e']$, between the two most prominent sets of $\{01\bar{1}2\}$ lamellae of each grain (fig. 21), is weak except in so far as it is conditioned by the orientation pattern of the *c* axes. From the distribution of these in figure 19 it is clear that all edges of the $[e{:}e']$ type must be concentrated in a broad belt corresponding to that of figure 21. In the Sonora arble one set of $\{01\bar{1}2\}$ lamellae, e_1, is outstandingly prominent in most grains; but the two remaining sets, e_2 and e_3, are clearly developed in many cases, so that selection of the second appropriate lamella for determination of $[e{:}e']$ may be arbitrary. There is a tendency to select from the two weaker sets of lamellae the one which is most nearly perpendicular to the plane of the section. Hence the respective maxima of the two partial diagrams constructed for differently oriented sections do not coincide; in each case the maximum within the broad concentration zone is biased toward the center of the diagram in question regardless of the orientation of the corresponding section.

Orientation phenomena in twinned grains

In both sections the measured grains of calcite may be divided arbitrarily into three equally well-represented groups: (1) grains with optically obvious strong twinning on $\{01\bar{1}2\}$; (2) "untwinned" grains in which all $\{01\bar{1}2\}$ lamellae, even where



prominently developed, appear (when the section is tilted to bring the lamellae into the vertical position) as sharp lines so that optical criteria of twinning are absent; (3) "slightly twinned" grains in which a few very narrow lamellae can be shown by their optical behavior to be twinned. To evaluate the role of twin gliding in development of $\{01\bar{1}2\}$ lamellae, grains of the first two categories were compared in detail (figs. 22-24). The contrasted distribution of points in figures 22 and 24 demonstrates a close correlation between degree of twinning and orientation of the corresponding space lattice within the rock fabric. Nearly all grains whose *c* axes lie in the vicinity of the points severally numbered 1 to 5 in figure 22 are strongly twinned. By contrast, most grains with *c* axes inclined at high angles to the foliation S_1 are "untwinned." The possibility that grains of the latter category are in fact completely twinned is discussed critically in a later section and is discarded for reasons given there.

As in the two previous marble fabrics described above, the restricted range of orientation of *c* axes in strongly twinned grains suggests that twinning has occurred in response to a simple system of applied stress applied to an aggregate of calcite grains whose lattices were already oriented as shown in figure 19. This possibility finds some support in the rather regular orientation of glide lines [*e*:*r*] in observed twin lamellae

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Figs. 22-27. Sonora marble, 55M50. Orientation of calcite. All diagrams projected on plane normal to strike of foliation S_1 (vertical), looking S20°E.

Fig. 22. *c* axes in 68 grains with strong $\{01\bar{1}2\}$ twin lamellae.

Fig. 23. Poles of $\{01\bar{1}2\}$ twin lamellae (78 in 68 grains). Lamellae falling in numbered areas belong to grains whose *c* axes fall in correspondingly numbered areas of figure 22.

Fig. 24. *c* axes in 63 untwinned grains (out of 150 measured).

Fig. 25. Glide lines $(01\bar{1}2):(10\bar{1}1)$ in 68 $\{01\bar{1}2\}$ twin lamellae. Contours at 4.5%, 1.5%, per 1% area.

Fig. 26. Axes of compression (dots) and tension (crosses) most favoring observed twinning on $\{01\bar{1}2\}$ in 68 individual grains. C and T are respective centers of concentration of compression and tension axes.

Fig. 27. Twinning in groups of grains numbered in figures 22 and 23: 1_c, 2_c, etc., are centers of *c* axis groups of figure 22. 1_e, 2_e, etc., are centers of corresponding groups of twin-lamella poles in figure 23. C_1, C_2 . . . . T_1, T_2, etc., are axes of compression and tension deduced from corresponding groups of *c* axes and twin lamellae; C and T are weighted centers of these stress-axes groups. The five arcs represent the statistical slip planes of the fabric whose poles are 1_e, 2_e, etc.; the numbered points 1, 2, etc., in these arcs are glide lines of the $(01\bar{1}2):(10\bar{1}1)$ type within these slip planes. β is the common intersection of four slip planes.

(fig. 25). It is strengthened greatly by the regular grouping of compression and tension axes most favorable to twinning, as determined graphically for individual twinned grains. These lie close to C and T, respectively, in figure 26.

Since the spread of *c* axes in twinned grains is greater than in the case of the other two marble fabrics described above, C and T have also been determined alternatively by somewhat different means. Take a group of *c* axes of generally similar orientation—e.g., points in the vicinity of 1 in figure 22.[1] Plot poles of observed $\{01\bar{1}2\}$ twin lamellae for all grains in the group. The lamella poles likewise are found to fall into a restricted area the center of which is about 26° from that of the *c*-axis group. Now determine graphically a compression and a tension axis appropriate for the whole group of grains (using the center of each group as the basis of construction). Centers of *c*-axis and lamella groups and corresponding tension and compression axes for the five numbered sectors of figure 22 are reproduced in figure 27. Centers of the resultant tension-axis and compression-axis concentrations (T and C) were determined taking into account the relative importance of each of the five groups. They closely approximate the corresponding axes C and T (determined by contouring) in figure 26. The great circles of figure 27 represent the five mean attitudes of $\{01\bar{1}2\}$ twin lamellae corresponding to the lamella concentrations numbered 1_e to 5_e. They can be regarded as five statistically defined discontinuous slip surfaces of the marble fabric. Mutual intersections of the four most important of these surfaces almost coincide at the point β, which has the same general significance as have β-axes determined by intersection of megascopic slip surfaces by the method of Sander (1948, p. 138). The existence of a β-axis of common intersection implies common origin of the slip surfaces in question (1, 2, 4, 5) under stresses applied at right angles to β. In all, 70 per cent of the measured strongly twinned grains have *c* axes and twin lamellae falling within the areas of concentration respectively designated 1_c, 2_c, 4_c, 5_c and 1_e, 2_e, 4_e, 5_e in figure 27. Mean glide directions (1, 2, 4, 5 in figure 27)

[1] The numbered areas of figure 22 are marked both by concentration of *c* axes of twinned grains and by absence of axes of "untwinned" grains. Three-quarters of the total axis points of figure 22 fall into the five areas selected.

for the four mean slip surfaces have been determined just as for individual twin lamellae. They are inclined to β at angles of $70° \pm 8°$.

Dynamic interpretation of twin lamellae

All of the data recorded for strongly twinned grains (figs. 22-27) can be explained by assuming simultaneous application of a compressional force in the general direction C and a tensile force approximating to T of figure 27. The assumed compression is nearly normal and the tension almost parallel to S_2. Now S_2 is essentially a plane of parallel elongation and slight displacement of calcite grains. In this respect, and in its relation to deduced compressive and tensile forces, it is reminiscent of the plane of rolling of a rolled metal fabric (Barrett, 1943, p. 406; McGeary and Lustman, 1950, pp. 6, 11); but in the Sonora marble the degree of "rolling" would be relatively slight.

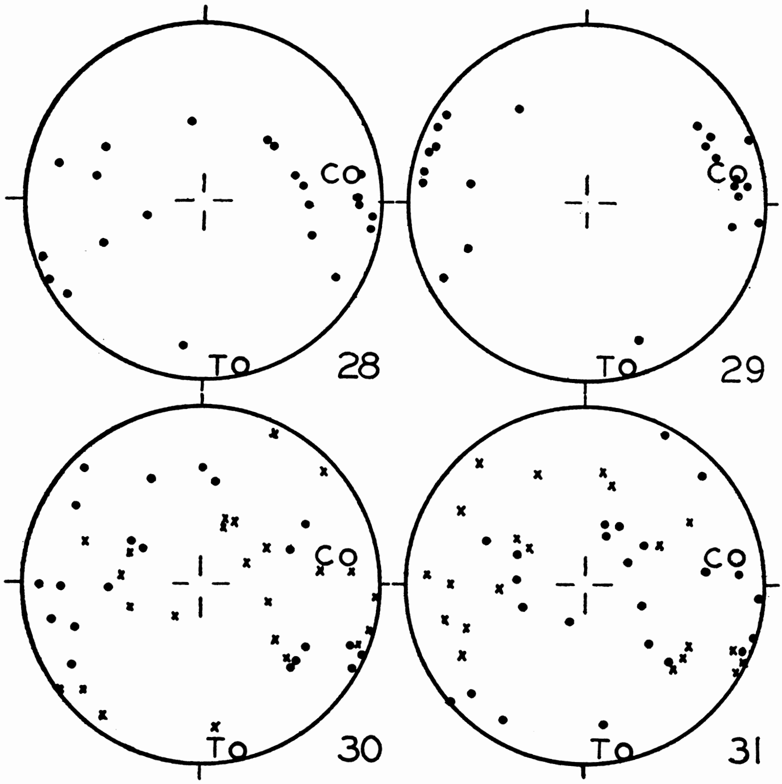
Geographically the deformation deduced from the twin-lamella fabric of Sonora marble may be described as a mild rolling out, under more or less lateral compression, on a plane dipping SW at 70°, with resultant extension of the rolled material approximately in the direction of dip. It cannot be correlated with the earlier and more important deformation responsible for the main foliation S_1.

Dynamic significance of untwinned grains

A scatter diagram for *c* axes in a random sample of untwinned grains is given in figure 28, and the poles of most prominent sets of $\{01\bar{1}2\}$ lamellae (one per grain) in the same grains are plotted in figure 29. In both diagrams the poles are clustered around C, the axis of compression deduced from the data referring to twinned grains. By analogy with the orientation data recorded for *c* axes and $\{01\bar{1}2\}$ lamellae in marble specimens deformed in the laboratory (Griggs, Turner, Borg and Sosoka, 1951, p. 1398), two alternative interpretations of figures 28 and 29 are possible: (1) the untwinned grains in the Sonora marble have failed to twin because their lattices are unfavorably situated within the stress field (Handin and Griggs, 1951, pp. 866-869); or (2) the *c* axes of figure 28 belong to lattices that have become completely twinned during deformation of the marble.

Two lines of evidence collectively support the first of these alternatives and render the second highly improbable:

(1) If the grains of figure 28 were completely twinned, we should expect to find other grains of similar orientation with strong lamellar twinning still recognizable. A glance at figures



Figs. 28-31. Sonora marble, 55M50. Orientation of calcite in a random sample of 22 untwinned grains (out of 79 measured). All diagrams projected on plane normal to strike of foliation S_1 (vertical), looking S20°E. C and T are compression and tension axes of figure 26.

Fig. 28. *c* axes.

Fig. 29. Poles of prominent {01$\bar{1}$2} lamellae (1 per grain).

Fig. 30. Compression axes (dots) and tension axes (crosses) most favoring twinning on {01$\bar{1}$2} lamellae of figure 29, assuming grains are essentially untwinned.

Fig. 31. Compression axes (dots) and tension axes (crosses) most favoring twinning on {01$\bar{1}$2} lamellae of figure 29, assuming grains are completely twinned.

22 and 24 shows that this is not the case: twinned and untwinned grains differ sharply in orientation.

(2) Assuming that the grains shown in figure 28 have become completely twinned on corresponding $\{01\bar{1}2\}$ lamellae recorded in figure 29, it is possible to construct graphically the original *c* axis of each grain, and then to determine the positions of the respective axes of compression and of tension that would be most effective in bringing about the assumed twinning. The compression and tension axes so determined are reproduced in figure 31. Not only do these show little regularity in their orientation, but there is no correlation between their distribution and the directions of compression and tension deduced from the partially twinned grains. If we are indeed concerned with completely twinned grains, then we must assume that the forces that brought about this twinning were directed at random and were in no way related to the uniformly directed forces responsible for partial twinning of other grains.

Finally there is the question of what dynamic significance may be attached to the prominent $\{01\bar{1}2\}$ lamellae observed in most untwinned grains. Do they represent incipient twinning, or are they products of some other mechanism of deformation? In figure 30 are plotted compression and tension axes favoring twinning on individual lamellae of figure 29, assuming that the grains are otherwise untwinned (i.e., that *c* axes of figure 28 are "original"). The points of figure 30 are so irregularly scattered and so little related to the corresponding points of figure 26 (twinned grains) that it is difficult to regard the linear lamellae of the untwinned grains as due to incipient twinning of the same kind as has given rise to strong lamellar twinning in twinned grains. Moreover the striking tendency for the lamella poles of figure 29 to cluster round the previously assumed compression axis C shows that these lamellae would be planes of low resolved shear stress under such compression, and so should be incapable of twinning. Why such visible lamellae develop on planes of low shear stress is still not understood. But it has been shown beyond doubt that in marble cylinders compressed or extended in such a direction that most grains are unfavorably oriented for twinning, linear lamellae similar to those of our present untwinned grains appear in greatest profusion on those $\{01\bar{1}2\}$ planes for which the resolved shear stress in the glide direction [*e*:*r*] approaches zero (Turner and Ch'ih, 1951, p. 899, fig. 6, no. 154).

It is concluded that the "untwinned" grains of the Sonora marble are in fact untwinned, and that the linear {01$\bar{1}$2} lamellae observed in them have developed under the same system of applied stress as was responsible for appearance of recognizable twinning in other grains.

CONCLUSIONS

(1) Many coarsely crystalline marbles lack obviously cataclastic structure and are remarkably homogeneous as regards preferred orientation of the *c* crystal axis of the calcite lattice. Careful measurement of 100 typical grains is sufficient to bring out the significant details of such a fabric, and serve as a basis for its dynamic interpretation in the light of what is known of the fabrics of experimentally deformed marbles.

(2) The preferred orientation pattern for *c* axes reflects that phase of metamorphism in which the grains assumed their present shape and size. In some cases, e.g., Yule marble described in this paper, the *c*-axis diagram is dominated by a concentration of axes at high angles to a foliation defined by parallel alignment of lenticular grains. Experiment shows that a similar concentration of *c* axes develops parallel to an axis of compression in marble deformed at temperatures of 300°C. or less. The natural fabric may be interpreted tentatively as having developed during compression normal to the foliation. But such an interpretation neglects the possible influence of recrystallization which undoubtedly played an important role in metamorphism but which took little or no part in the process of experimental deformation. To the writer it seems probable that the main effect of recrystallization synchronous with deformation is somewhat to weaken an orientation pattern which would otherwise have developed to a higher degree by purely mechanical processes (twin gliding, translation gliding, rotation of grains, and so on). This view, admittedly speculative, is based on the rather weak concentrations of *c* axes in many well-foliated marbles, as contrasted with stronger concentrations achieved in marble cylinders shortened by 30 per cent or less in the laboratory.

(3) Visible lamellae in all marbles described in this paper are almost exclusively parallel to {01$\bar{1}$2} of the calcite lattice.

Some grains show a superficially similar lamellar parting parallel to a $\{10\bar{1}1\}$ face. Lamellae of other crystallographic orientations have been searched for, but are absent.

(4) The *c* axes and the $\{01\bar{1}2\}$ lamellae of grains with optically recognizable $\{01\bar{1}2\}$ twins have a restricted range of orientation as compared with the range of the same crystal elements for twinned and untwinned grains of the same rock considered collectively. This restricted range of orientation for twinned grains may be explained on the assumption that twinning developed in the last stages of deformation under a simple system of applied stress. The nature of this stress is readily deduced from consideration of orientation data referring to twinned crystals.

(5) Grains whose lamellae are not optically recognizable as twins are in most cases untwinned rather than completely twinned crystals with reference to post-crystalline deformation. The visible $\{01\bar{1}2\}$ lamellae within them may be correlated with the same stress system as was effective in causing twinning in other grains. The most prominent sets of $\{01\bar{1}2\}$ lamellae of untwinned grains are aligned at high angles to the deduced direction of compression, i.e., in planes of low shear stress.

(6) The direction and nature of late applied stress deduced from twinning hold good within a hand specimen. Whether they may remain constant over larger fields has not yet been tested. Further investigation of this phase of the problem by D. B. McIntyre and the writer is now in progress.

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