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PRESSURE DEPENDENCE OF QUARTZ DEFORMATION LAMELLAE ORIENTATIONS

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ABSTRACT. Experiments on Canyon Creek quartzite have been conducted at a constant strain rate of 7.8 • 10^{-6}/sec in the temperature range 600° to 1050°C and confining pressure interval 4 to 20 kb to test for a pressure dependence of quartz deformation lamellae orientations. Four distinct orientations, strongly dependent on temperature and pressure, are recognized: (1) basal (high pressure, low temperature); (2) prismatic (high temperature, low pressure); (3) subbasal I (moderate temperature, low pressure); and (4) subbasal II (high temperature, high pressure). In addition, a fifth field in which lamellae form at all orientations (moderate temperature, low pressure) overlaps the prismatic–subbasal I-II fields. The subbasal I lamellae are identical in optical properties and orientations to most deformation lamellae in quartz-bearing tectonites. The results from this and a previous study (Heard and Carter, 1968) suggest that at strain rates lower than about 10^{-13}/sec subbasal I lamellae should form at all crustal pressures to about 500°C. The presence of H_2O, although drastically weakening the quartzite mechanically, does not appear to affect the P–T fields of the various mechanisms. It is suggested, by analogy with preliminary experimental studies on BeO and beryl crystals, that subbasal lamellae may form only in crystals lacking a basal plane of symmetry.

INTRODUCTION

The important question of plastic deformation mechanisms in naturally deformed quartz polycrystals has received much attention in the last decade in studies by many both on experimentally and naturally deformed aggregates. Of the various subfabric elements produced by intragranular flow, most work has been done on the nature, orientation, and dynamic significance of deformation lamellae in quartz. Turner's (1948) suggestion that quartz lamellae originate by plastic flow in planes of high shearing stress has since been confirmed by many studies, and various methods have been established for determining principal stress directions from lamellae orientations and their relations to other subfabric elements (for a recent review, see Carter and Raleigh, 1969). The nature and orientation of most natural lamellae have been described in detail elsewhere (for example, Christie, Griggs, and Carter, 1964; Carter and Friedman, 1965; Heard and Carter, 1968). In summary (A) they are sub-planar features, most profusely developed in highly deformed zones, symmetrical and brighter than the host in bright field, and asymmetrical in phase contrast illumination; (B) most commonly they seem to be non-rational, being inclined to the basal plane {0001} at angles ranging from 10° to 30°.

Deformation lamellae were first produced in experiments on quartz sand, quartzite, and quartz single crystals deformed at 5 to 30 kb confining pressure, temperatures from 300° to 1700°C at strain rates of about 10^{-4} to 10^{-8}/sec (Carter, Christie, and Griggs, 1961, 1964; Heard, ms; Christie, Griggs, and Carter, 1964; Griggs and Blacic, 1964; and Christie

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and Green, 1964). In the polycrystals and single crystals oriented best for basal slip, the quartz deformed predominantly by slip on the basal plane parallel to an *a*-axis at temperatures below about 750°C. Thin sections revealed the presence of deformation lamellae, optically similar to those of naturally deformed quartz, oriented nearly parallel to the basal plane. The basal lamellae were shown by photoelastic and etch pit studies to be consistent with stress-birefringence effects expected from trapped slip dislocation arrays (Christie, Griggs, and Carter, 1964). This interpretation was confirmed by transmission electron microscope studies on some of the specimens by McLaren and others (1967) and on plastically deformed synthetic quartz (McLaren and Retchford, 1969).

In naturally deformed rocks, basal quartz lamellae are common only to quartz shocked by meteorite or comet impact (Carter, 1965, 1968). Deformation lamellae of the subbasal type observed in tectonites were first reported by Heard (ms) in dry experiments on quartzite at 5 kb confining pressure, 300° to 500°C, and strain rates of 10^{-7} to 10^{-8}/sec. They have also been produced in more extensive recent dry experiments on quartz crystals and quartzite at confining pressures of 6 to 10 kb, temperatures from 500° to 1020°C, and strain rates ranging from about 10^{-3} to 10^{-7}/sec (Heard and Carter, 1968). From single crystal studies it was found that the lamellae are indeed non-rational, and from both single crystal and polycrystal studies it was observed that the lamellae are almost invariably oriented closer to σ_1 than is the basal plane and are most commonly inclined to σ_1 at angles less than 45°. At the lower temperatures and higher strain rates this subbasal mechanism gave way to a basal slip mechanism, and at higher temperatures and lower rates to a process whereby lamellae form at all crystal orientations (Heard and Carter, 1968, fig. 11A).

In addition to the temperature and strain rate dependence of the flow mechanisms a rather definite pressure dependence was observed over the small pressure interval 6 to 10 kb (Heard and Carter, 1968, fig. 18B). An extrapolation of the pressure-temperature boundary separating the field of basal slip from that of the subbasal mechanism to 15 kb suggested that the subbasal mechanism should predominate at temperatures above about 700°C, whereas Griggs and Blacic (1964) observed predominant prismatic slip in their experiments on single crystals. This discrepancy in addition to other indications that the quartz deformation mechanisms might be pressure sensitive prompted the present investigation. We shall show that the orientations of deformation lamellae in quartz are indeed strongly pressure dependent, although the physical basis for this dependence is not yet understood.

THE EXPERIMENTS

We have conducted thirty-two experiments on Canyon Creek quartzite in the confining pressure range 4 to 20 kb, temperatures of 600° to 1050°C at a constant strain rate of $7.8 \cdot 10^{-6}$/sec (table 1). Cylindrical cores (0.1 in. diam by 0.3 in. long) of the equiaxial, fairly fine-grained

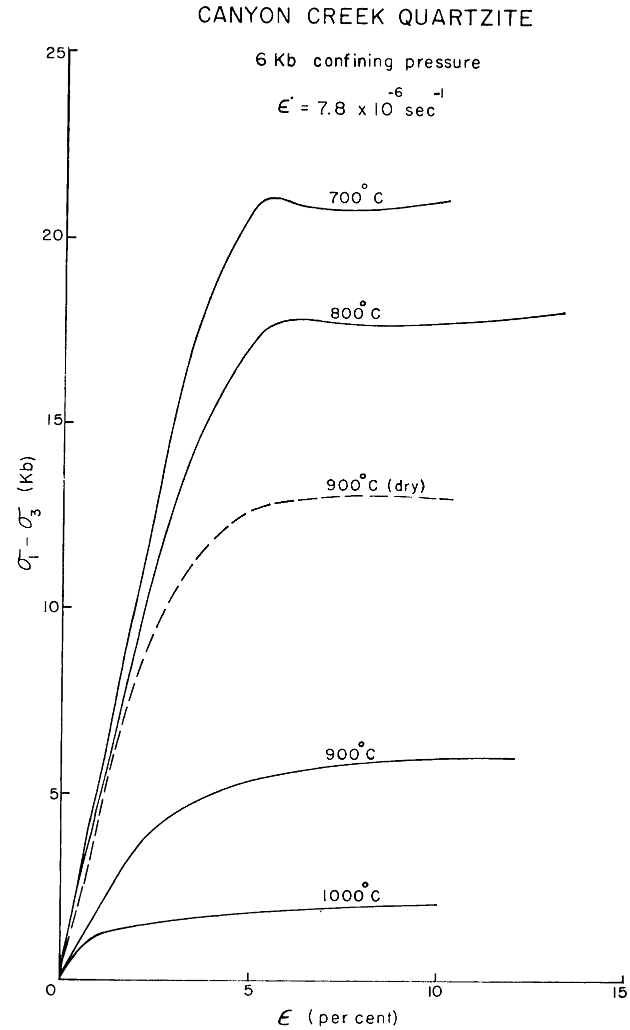


Fig. 1. Stress-strain curves showing mechanical properties of Canyon Creek quartzite at a strain rate of $7{\cdot}8 \times 10^{-6}$/sec at various temperatures. The large drop in strength at 800°C is due to release of H_2O by alteration of the talc confining medium.

(0.1 mm avg) Canyon Creek quartzite were permanently deformed in compression by about 10 percent in a solid pressure medium, constant strain rate apparatus designed by Griggs (1967). The pressure medium used in most of the experiments was talc, so that at temperatures above about 800°C, H_2O was released due to talc alteration. This resulted in the drastic mechanical weakening shown in figure 1, an important feature discovered by Griggs and Blacic (1965) and discussed in more detail by Griggs (1967) and McLaren and Retchford (1969). Two experi-

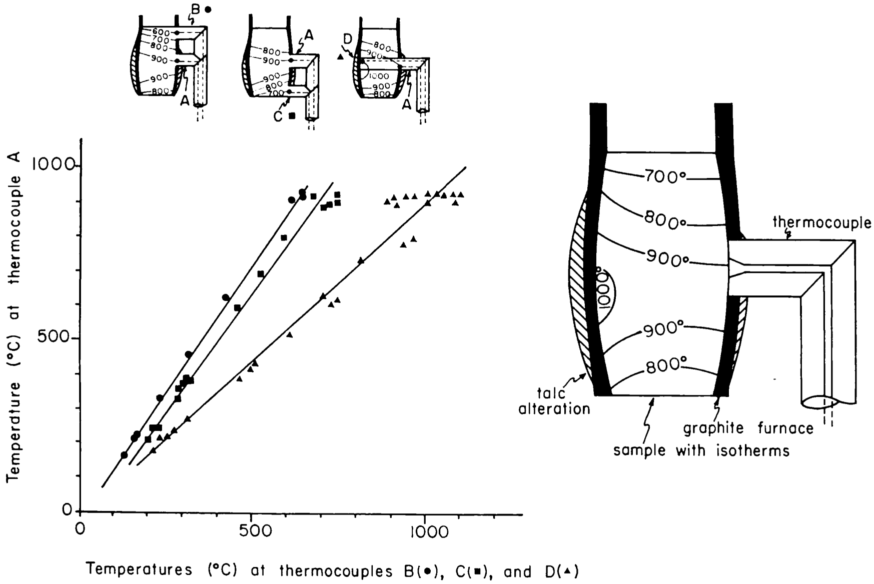


Fig. 2. Temperatures in various parts of the sample (upper left) plotted against temperature at reference thermocouple (A). Isotherms constructed on basis of results and talc alteration zone shown for sample deformed at 900°C (at right).

ments were done with an insert of anhydrous AlSiMag–222 placed between the graphite furnace and talc at 900°C to compare the operative slip mechanisms in the presence and absence of H_2O. As is evident from the figure, the specimen deformed dry at 900°C (dashed line; N-123) is appreciably stronger than that deformed in the presence of H_2O. All our specimens deformed dry are stronger than the Simpson orthoquartzite at comparable conditions (Heard and Carter, 1968). This discrepancy may be accounted for by one or a combination of the following factors: (A) differences in initial H_2O content; (B) the finer grainsize of the Canyon Creek quartzite (0.1 mm versus 0.2 mm); and (C) differences in apparatus.

Because of the sample assembly geometry, there is a large longitudinal thermal gradient and a moderate radial gradient in our experiments. We have attempted to calibrate the temperature distribution in the sample at various nominal reference thermocouple temperatures in the manner shown in figure 2. The resulting isothermal configurations as deduced from the calibrations and widths of talc alteration zones are shown in the figure (right). The uneven distribution of the isotherms necessitated careful sampling in discrete regions within which a statistically significant sample could be obtained within reasonably narrow temperature limits. This procedure is illustrated in figure 3 where data for all grains in region C at temperatures greater than 800°C are separated from data obtained from regions T and B, where the tempera-

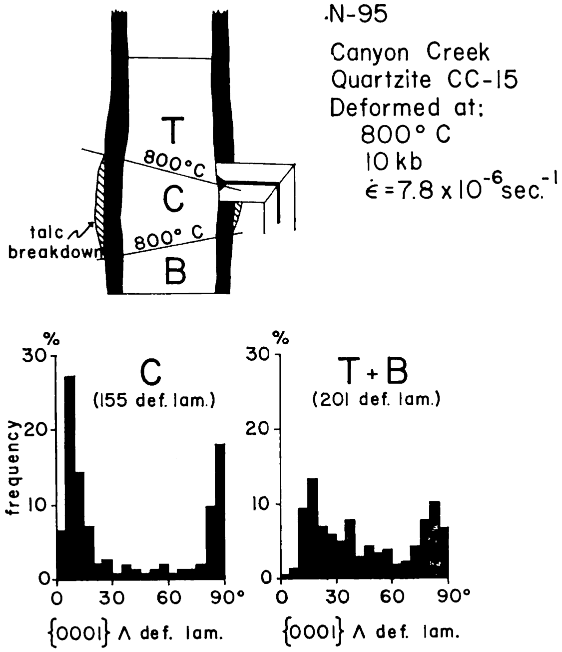


Fig. 3. Orientations of deformation lamellae (lower) determined by sampling area C (left) and T and B (right) in specimen N-95 (top).

ture interval sampled was about 600° to 800°C; note the difference in lamellae orientations in the two regions. Ten of the specimens listed in table 1 were analyzed in this fashion with the temperature interval in the sampled regions indicated (T + B = a; C = b) as based on the calibrations. Specimens not analyzed in this manner were sampled only near the center with the expected temperature interval given in the table.

The results of this study are plotted in the pressure-temperature diagram in figure 4. The histograms showing orientations of lamellae are placed near the center of the temperature interval indicated in table 1 and by the vertical lines with arrowheads drawn through the center of each histogram. On the basis of the orientations of the deformation lamellae we have subdivided the diagram into four fields, each with different lamellae orientations although there are gradations between some of these, such as the prismatic-subbasal II fields. From these raw data (fig. 4) and the synoptic data presented in figure 5, the four subfields are: (1) basal (low temperature and high pressure; fig. 5A)—there is a pronounced maximum of lamellae inclined at less than 5° to {0001}; (2) prismatic (high temperature, low pressure; fig. 5B)—a strong concentration at 81° to 90° to {0001} with a submaximum at 0° to 15°; (3) subbasal II (high temperature, high pressure; fig. 5C)—a concentration between 0° and 15° with a strong maximum between 5° and 10° and a

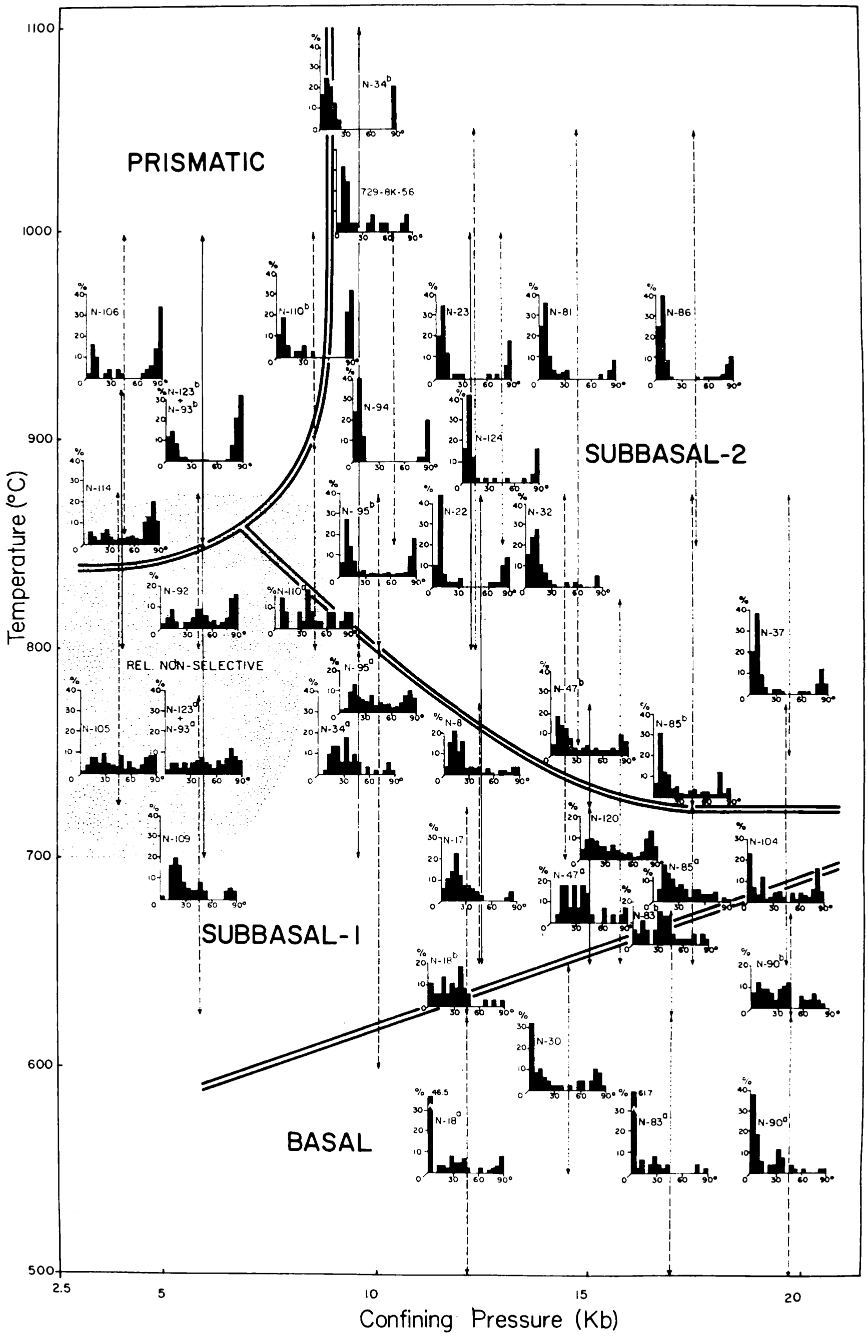


Fig. 4. Diagram showing orientations of lamellae as a function of temperature and pressure. The diagram has four subfields as shown and a fifth (stippled) overlapping three others (see text).

TABLE 1

Number of experiment	T (°C)	Temperature range	P (kb)	Total ε(%)	Assembly	Number of sets of deformation lamellae measured	Predominant mechanism
N-30	600	550-650	14.6	21.6	t	50	B
N-83	600	500-625(a)	17.0	9.7	t	47	B
		625-675(b)				46	SB I
N-90	600	450-625(a)	19.8	8.8	t	53	B
		625-675(b)				59	SB I
N-18	650	500-625(a)	12.2	16.1	t	86	B
		625-725(b)				37	SB I
N-109	700	625-775	5.9	10.6	t	75	SB I
N-17	700	650-775	12.5	16.6	t	66	SB I
N-47	700	650-725(a)	15.1	12.4	t	29	SB I
		725-775(b)				64	SB II
N-104	700	650-775	19.7	10.2	t	100	B (P)
N-120	750	650-825	15.8	10.2	t	297	SB I
N-105	800	725-875	4.0	14.4	t	100	R
N-92	800	800-875	5.9	13.3	t	100	R
N-95	800	650-800(a)	10.1	13.6	t	201	SB I (P)
		800-875(b)				155	SB II (P)
N-8	800	650-875	12.5	14.3	t	100	SB II (SB I)
N-32	800	700-875	14.5	17.1	t	91	SB II
N-85	800	650-725(a)	17.5	13.4	t	104	SB I
		725-875(b)				136	SB II
N-87	800	750-875	19.7	15.4	t	100	SB II
N-114	850	800-925	4.0	10.1	t	191	P (R)
N-106	900	850-1000	4.1	10.3	t	50	P (SB II)
N-123	900	700-850(a)	6.0	10.5	A	68	R
		850-1000(b)				100	P (SB II)
N-93	900	750-850(a)	6.0	13.6	t	110	R
		850-1000(b)				96	P (SB II)
N-110	900	800-900(a)	8.6	7.2	t	27	R
		900-1000(b)				38	P (SB II)

N-94	900	850-1000	10.4	12.6	t	50	SB II (P)
N-22	900	800-1000	12.3	17.8	t	50	SB II (P)
N-124	900	850-1000	13.0	7.6	A	50	SB II (P)
N-23	950	800-1050	12.3	18.0	t	50	SB II (P)
N-81	950	750-1050	14.8	9.9	t	100	SB II (P)
N-86	950	850-1050	17.5	16.2	t	100	SB II (P)
N-88	950	850-1050	20.0	14.0	t	—	recrystallized
N-116	1000	900-1100	5.1	10.7	t	few	(P, SB II)
N-34	1000	700-800(a)	9.6	16.0	t	51	SB I
		800-1100(b)				24	SB II (P)
729-BK-56*	1000	—	10		*	25	SB II
N-10	1000	850-1100	12.5	8	t	—	recrystallized
N-33	1050	900-1150	15.8	17.7	t	—	recrystallized

Experiments at = $7{\cdot}8 \times 10^{-6}$ sec^{-1} on Canyon Creek Quartzite
Temperature range: (a) top and bottom
(b) central part of sample
Assembly: t = talc
A = talc + AlSiMag
Predominant mechanism:
B = Basal
SB I = Subbasal I
SB II = Subbasal II
P = Prismatic
R = Relatively non-selective
* Simpson quartzite, deformed in gas-apparatus, Cu-capsule, $\dot{\varepsilon} = 3 \times 10^{-6}$ sec^{-1}, (Heard and Carter, 1968).

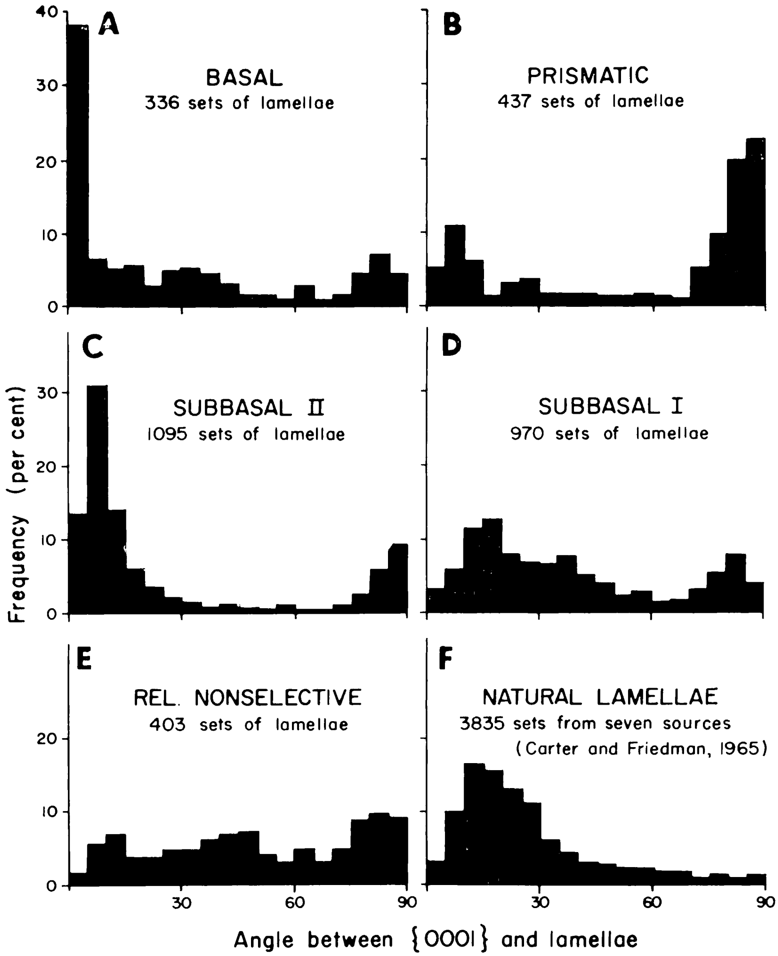


Fig. 5. Synoptic histograms showing orientation of lamellae in the four subfields of figure 4 (A,B,C,D) and stippled area (E). Histogram (F), a compilation of naturally produced lamellae from seven sources, compares well only with subbasal I diagram (D).

submaximum at 81° to 90°; and (4) subbasal I (moderate temperature, low pressure; fig. 5D)—a strong concentration in the range 10° to 40° with a maximum between 10° and 20° and a submaximum between 75° and 85°. In addition to the foregoing, we have stippled in figure 4 the low pressure-moderate temperature field in which we observe lamellae at all orientations (fig. 5E; termed "relatively nonselective" by Heard and Carter, 1968). Deviations of a few of the histograms from ideal orientations in the various subfields are ascribed to improper thermocouple placement (recorded temperature less than actual temperature as in N-90) and to sampling problems (for example, too few lamellae as in N-47a).

The orientations of 3835 sets of deformation lamellae in tectonites from seven sources (Carter and Friedman, 1965) are shown in figure 5F for comparison with the lamellae experimentally produced during the present study. It is evident that the orientation of subbasal I lamellae (fig. 5D) corresponds most closely with the natural orientations, although the incidence of subprismatic lamellae is somewhat higher. Many other published studies not included in figure 5F show virtually the same results. Two exceptions to this are orientations observed by Preston (1958) and Sylvester (1969) which show essentially bimodal distributions with peaks at about 30° and 60° to {0001}. Such orientations have no counterpart in the experimentally produced lamellae and, to date, are not understood.

In addition to similarities in the orientation of subbasal I lamellae to those in tectonites, the relative orientation of the various subfabric elements are the same (see for example, Carter and Friedman, 1965; Heard and Carter, 1968). The arrows in figure 6A connect the poles to lamellae (heads) to *c*-axes (ends) in zones containing lamellae in individual grains. On the basis of earlier work these arrows should tend to point toward σ_3 or the $\sigma_2 = \sigma_3$ plane, as they clearly do. A similar tendency is noted for grains containing subbasal II lamellae (6° to 15°; fig. 6B), the significance of which will be commented on subsequently.

DISCUSSION OF THE RESULTS

The synoptic diagram in figure 7 shows the confining pressure and temperature dependence of the orientations of deformation lamellae in quartz as deduced from this study. Included in the diagram are the results (circles) of dry experiments on quartzite deformed at 6 to 10 kb in a gas apparatus (Heard and Carter, 1968). In general the results of the two studies are in excellent accord, although we observe predominantly prismatic slip in the high temperature regime where Heard and Carter (1968) observed the relatively nonselective mechanism. We have observed the latter at somewhat lower temperatures (fig. 4), overlapping the subbasal I-II-prismatic fields.

To test further the effect of H_2O released from talc alteration on the pressure-temperature fields of the various mechanisms, we did two dry experiments (N-123, N-124) at 900°C using an AlSiMag insert. The results for N-93 (wet) and N-123 (dry), both deformed at 900°C, 6 kb are shown in figure 8. The data from the central and tops and bottoms of the two specimens are virtually identical confirming inferences drawn from comparisons of our data and the dry data of Heard and Carter (1968). Specimen N-124, deformed dry at 900°C at 13 kb was sampled near the center and shows the same (subbasal II; fig. 4) mechanism as samples deformed wet under similar conditions. Thus, although the presence of externally released H_2O has lowered the strength of N-93 very markedly (solid line, fig. 1) by comparison with N-123 (dashed line, fig. 1), it appears to have little effect on the pressure-temperature fields of the lamellae orientations.

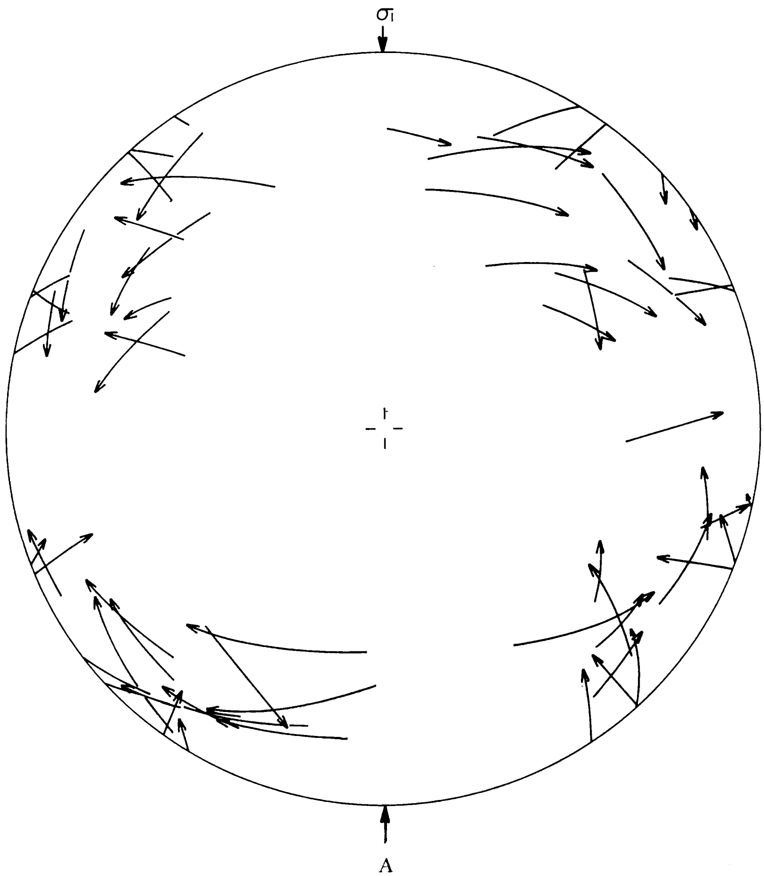
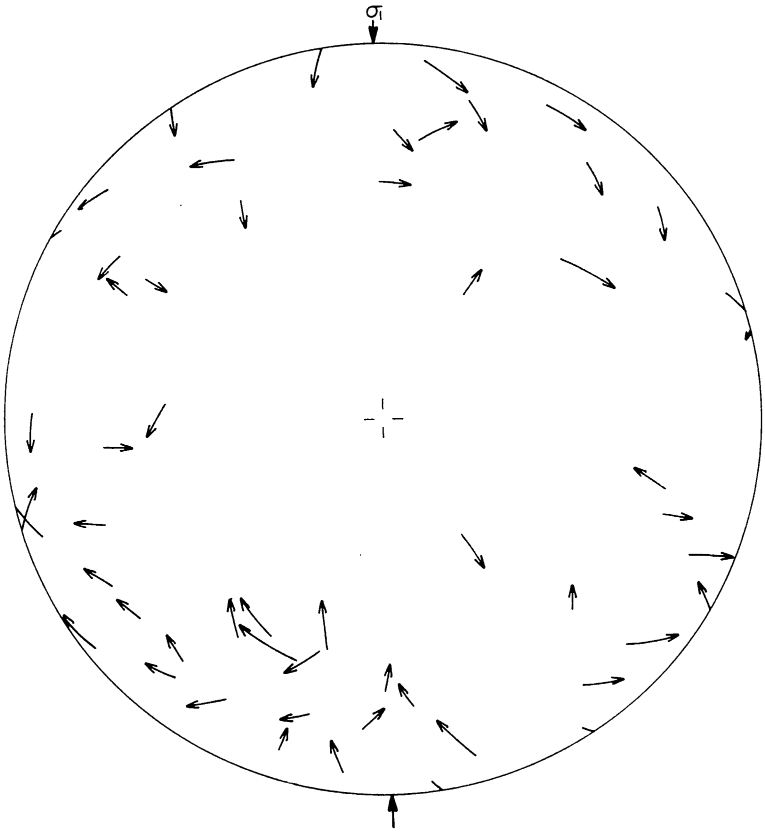


Fig. 6. Arrow diagrams for specimens N-109 (A) and N-86 (B); lower hemisphere equal area projections, σ_1 is oriented north-south. Heads of arrows show orientations

Therefore, on the basis of these consistent results, we feel justified in presenting a tentative schematic plot (fig. 9) in pressure–temperature–log strain rate space of the combined results of this study and that of Heard and Carter (1968). The transition temperature from basal slip to the important subbasal I mechanism drops moderately with decreasing pressure but drops greatly with decreasing strain rate. Thus, at representative geological strain rates of about 10^{-13} to 10^{-15}/sec, subbasal I lamellae would be expected to form during deformation at temperatures to about 500°C at crustal pressures. This, we feel, explains the great preponderance of lamellae of this orientation in tectonites.

The physical mechanism whereby subbasal I lamellae originate is still enigmatic. Christie, Griggs, and Carter (1964) suggested that: (A) the lamellae may have been internally rotated from a basal orientation by slip on a secondary system or (B) the subbasal lamellae may be *en*



of poles to lamellae and ends represent *c*-axes. Arrows for both subbasal I (A) and subbasal II (B) lamellae tend to point toward $\sigma_2 = \sigma_3$ plane.

echelon arrays of basal edge dislocations. The first of these requires rather large strains and hence changes in grain shape (Carter, Christie, and Griggs, 1964), a feature that is not observed in many of the studies to date. Carter, Christie, and Griggs, (1964) and Heard and Carter (1968) have tried to check the second hypothesis by extensive attempts to etch and replicate natural lamellae and subbasal I lamellae produced experimentally in quartz crystals. The experimentally produced lamellae did not etch differentially at all, and considerable difficulty was encountered etching and replicating natural lamellae. Therefore, the second hypothesis (B) has not yet been confirmed.

Heard and Carter (1968) suggested that frictional forces might be important in subbasal I lamellae formation mainly on the basis of the confining pressure dependence and the fact that the lamellae form statistically at 30° to 40° to σ_1. These angles are typical of faults in

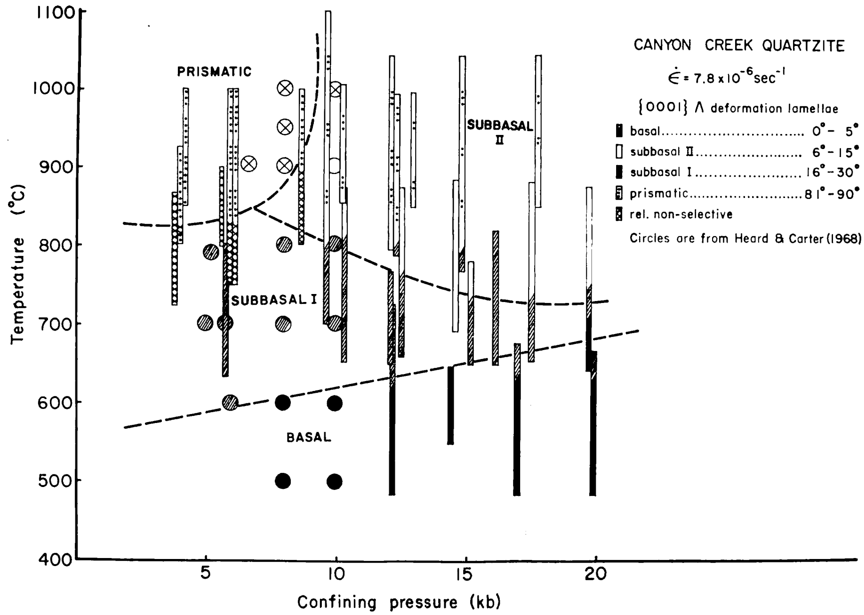


Fig. 7. Synoptic diagram showing results of this study (vertical bars) in comparison with the dry results (circles) of Heard and Carter (1968).

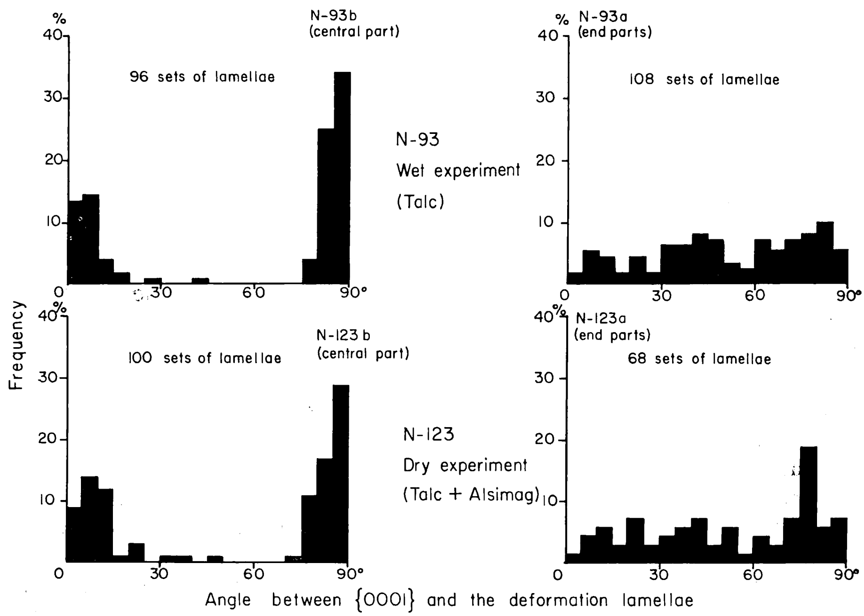


Fig. 8. Histograms showing lamellae orientations in central part (left) and top and bottom parts (right) of specimens N-93 (deformed wet) and N-123 (deformed dry) both deformed at 900°C, 6 kb, and a strain rate of 7·8 × 10^{-6}/sec.

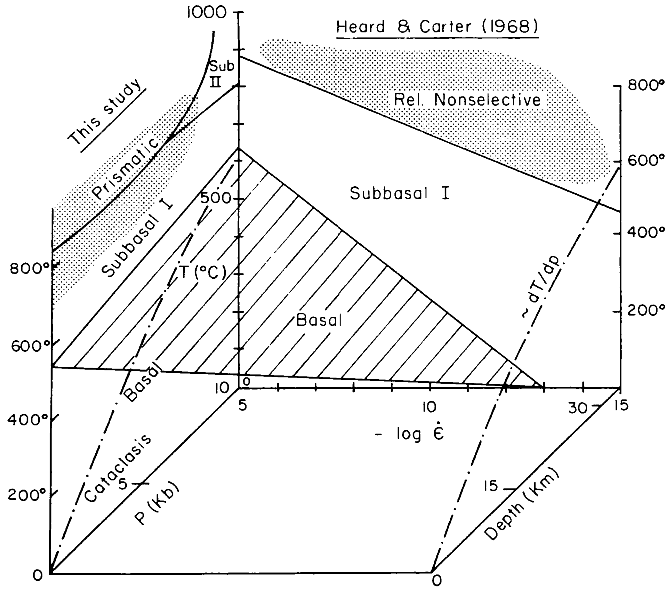


Fig. 9. Schematic diagram showing the results of this study to 10 kb (P–T plane, left) and extrapolated results of Heard and Carter (1968; T —log $\dot{\varepsilon}$ plane, right). The hatched triangle represents a plane in —log $\dot{\varepsilon}$ — P–T space below which basal lamellae predominate and above which the subbasal I and other mechanisms predominate. The dashed-dotted curve labeled dT/dp shows a possible continental geotherm (Clark and Ringwood, 1964).

mechanically isotropic aggregates for which there is a demonstrable normal stress dependence. Their results showed, however, that the lamellae are not related to simple frictional phenomena, independent of the crystal structure. Nor are they simple plastic flow phenomena; the lamellae do not originate by trapping slip dislocations moving in these non-rational planes. We had sought to resolve this question by measurements of changes in yield stress with pressure, and, although there may be a suggestion of a strength increase with increasing pressure, the mechanical data are not sufficiently reproducible to warrant presentation or further discussion.

A more elegant hypothesis of the origin of subbasal lamellae has been presented by Christie, Tullis, and Blacic (1968). In their model the subbasal lamellae are created by the climb (or in some cases cross-slip) of basal slip dislocations due to the diffusion of interstitial atoms. They observed a dependence of the angle between lamellae and {0001} on H_2O content in the experimentally deformed crystals and suggested that H_2O diffusion is the controlling mechanism. Although attractive, two observations from the present study suggest that this model may not be applicable to the origin of all subbasal lamellae. First, we would expect a progression with increasing temperature at constant strain rate and pressure from a basal mechanism through a subbasal II mechanism to a subbasal I mechanism; that is, the inclination to {0001} of the lamellae should increase with increasing temperature, a feature that is not observed in our experiments (figs. 4 and 7). A possible change in mechanism at the higher temperatures (subbasal II regime) from interstitial to vacancy diffusion should lead to a tendency for the lamellae to be oriented farther from σ_1 than the basal plane, a tendency that is not observed in figure 6B or in any of our specimens deformed in the subbasal II regime. Secondly, experiments at 900°C in the presence and absence of externally released H_2O show virtually the same lamellae orientations (fig. 8). At this temperature and strain rate the quartzite in the presence of externally released H_2O is in the water-weakened state (fig. 1; Griggs, 1967, fig. 3), and we might expect the lamellae to be at higher inclinations to {0001} than in the dry experiments. Subbasal I lamellae were also produced at 900°C in about 100 sec in two dry experiments on quartz crystals (Heard and Carter, 1968) implying the very rapid diffusion rate of order 10^{-9} cm^2/sec ($D \approx 1/3\ hl^2$; Cottrell, 1964, p. 201), if the climb hypothesis is to be maintained.

Indirect, but relevant, observations have recently been obtained from dry compression experiments on BeO crystals deformed at 10 kb confining pressure, strain rates near 10^{-4}/sec, and at temperatures of 25°C, 300°C, 500°C, and 800°C (Heard and Carter, in preparation). The crystals were oriented so that either an *a*-axis or *m* (*a**) axis in the basal plane had the maximum resolved shear stress coefficient. Lamellae were not produced in the room temperature experiments, but external rotations resulting in undulatory extinction were consistent with slip on the system {0001} [11$\bar{2}$0]. In both experiments at 300°C, well developed deformation lamellae, identical to those in quartz, were inclined at 10° to {0001} (subbasal II-I range). The relative orientations, with respect to the stress, of the lamellae and basal plane were also the same as in quartz. Subbasal lamellae were weakly developed in the experiment at 500°C, and no lamellae were observed in the experiment at 800°C. At 300°C, the ratio of the ambient temperature to the melting temperature (T/Tm, °K) is about 0.2, and hence it is very unlikely that the diffusional process of dislocation climb could have been important at these deformation rates (see, for example, Sherby and Burke, 1968).

What physical process(es) then is responsible for the origin of these non-rational subbasal lamellae? We do not have the answer to this important question, but we suspect that the solution will involve interactions of dislocations with basal twins found both in quartz and BeO. That is, we suggest that the lack of a plane of symmetry parallel to {0001} in quartz (class 32)[1] and BeO (class 6 mm) is of fundamental im-

[1] Quartz (trigonal class 32) inverts by displacive transformation to the β-phase (hexagonal class 622) at a critical temperature depending on the confining pressure and differential stress (Coe and Peterson, 1969). A basal plane of symmetry is still lacking, and Brazil twins may persist (Frondel, 1962) but of course, Dauphiné twins are lost. However, if the data of Coe and Peterson (1969) at 3 kb are extrapolated to the higher pressures of our experiments, it is found that both the subbasal I and II fields remain in the α-quartz stability field.

portance to the origin of subbasal lamellae. McLaren and others (1967) have shown, by transmission electron microscopy, that Brazil twins parallel to {0001} (some containing or terminated by dislocations) were produced at high shearing stress in experiments on single crystals at 500° and 700°C (basal slip regime). These authors showed that the twins could be produced mechanically by a translation of about 1/2 *a* and that only the hand of the crystal within the twinned region is changed. More recently, Tullis (1970) has shown that Dauphiné twins in quartz can be produced mechanically with ease. In this instance, the polarity of the *a*-axes is reversed so that negative forms become positive and vice versa, and this process gives rise to preferred orientations of $\perp$ *r* $\{10\bar{1}1\}$ parallel to σ_1.

Recent work on bromellite (BeO; Newkirk and Smith, 1965) has also shown the presence of extensive inversion twins parallel to the basal plane. As pointed out by Bentle and Miller (1967) such a twin boundary becomes impregnable to dislocations with Burgers vectors normal to the boundary because beryllium atoms at the edge of the half-planes are forced against those of the twin causing mutual repulsion. They also showed that the inversion twins and cores of high densities of point defects, probably impurities, interferred with basal slip in the crystals. In a similar manner, complex interactions of basal and prismatic dislocations in quartz with basal twins and impurity concentrations could account for the non-rational subbasal lamellae.

In order to test the notion that the basal twins in quartz and BeO may affect lamellae orientations, we conducted a series of experiments on beryl (class 6/m, 2/m, 2/m) whose basal plane is a symmetry plane. The experiments were carried out in compression at 15 kb confining pressure, a strain rate of $7.8 \cdot 10^{-5}$/sec, and temperatures of 300°, 600°, 900°, and 1200°C (the melting temperature of beryl is about 1420°C). Faults parallel to {0001} were produced at 300°C. In the experiments at 600° and 900°C both basal faults and basal deformation lamellae were abundant. In the final experiment at 1200°C, only basal lamellae were observed. Subbasal lamellae were not produced in any of the experiments, in accord with our prediction.

We suggest, therefore, on the basis of the circumstantial evidence presented above, that the lack of a symmetry plane parallel to the base is likely to be involved in the origin of subbasal lamellae. We note that Borg and Heard (1970) have also observed subbasal deformation lamellae in their compression experiments on plagioclase at 10 kb confining pressure, 800°C, and a strain rate of 10^{-5}/sec. Lacking the critical evidence, which must come from painstaking transmission electron microscopy of both experimentally and naturally deformed materials, we do not wish to propose a specific model for the origin of subbasal lamellae. However, any detailed future model must account for the observations discussed above as well as the profound pressure, temperature, and strain-rate dependences of quartz lamellae orientations.

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REFERENCES

Bentle, G. G., and Miller, K. T., 1967, Dislocation, slip and fracture in the BeO single crystals: Jour. Appl. Physics, v. 38, p. 4248-4257.

Borg, I. Y., and Heard, H. C., 1970, Experimental deformation of plagioclases, *in* Paulitsch, P., ed., Experimental and Natural Rock Deformation (Bruno Sander birthday volume): Berlin-Heidelberg-New York, Springer-Verlag, p. 375-403.

Carter, N. L., ms, 1963, Experimental deformation and recrystallization of quartz: Ph.D. thesis, Univ. Calif. Los Angeles, Los Angeles, Calif., 213 p.

——— 1965, Basal quartz deformation lamellae—a criterion for recognition of impactites: Am. Jour. Sci., v. 263, p. 786-806.

——— 1968, Dynamic deformation of quartz, *in* French, B. M., and Short, N. M., eds., Shock Metamorphism of Natural Materials: Baltimore, Maryland, Mono Book Corp., p. 452-474.

Carter, N. L., Christie, J. M., and Griggs, D. T., 1961, Experimentally produced deformation lamellae and other structures in quartz sand: Am. Geophys. Union Trans., v. 42, p. 229.

——— 1964, Experimental deformation and recrystallization of quartz: Jour. Geology, v. 72, p. 687-733.

Carter, N. L., and Friedman, Michael, 1965, Dynamic analysis of deformed quartz and calcite from the Dry Creek Ridge Anticline, Montana: Am. Jour. Sci., v. 263, p. 747-785.

Carter, N. L., and Raleigh, C. B., 1969, Principal stress directions from plastic flow in crystals: Geol. Soc. America Bull., v. 80, p. 1231-1264.

Christie, J. M., and Green, H. W., 1964, Several new slip mechanisms in quartz [abs.]: Am. Geophys. Union Trans., v. 45, p. 103.

Christie, J. M., Griggs, D. T., and Carter, N. L., 1964, Experimental evidence of basal slip in quartz: Jour. Geology, v. 72, p. 734-756.

Christie, J. M., Tullis, J. A., and Blacic, J. D., 1968, The non-rational nature of deformation lamellae in quartz [abs.]: Am. Geophys. Union Trans., v. 49, p. 314.

Clark, S. P., Jr., and Ringwood, A. E., 1964, Density distribution and constitution of the mantle: Rev. Geophysics, v. 2, p. 35.

Coe, R. S., and Peterson, M. S., 1969, The α-β inversion in quartz: A coherent phase transition under non-hydrostatic stress: Jour. Geophys. Research, v. 74, p. 4921-4948.

Cottrell, A. H., 1964, The mechanical properties of matter: New York, John Wiley and Sons., 430 p.

Frondel, Clifford, 1962, Dana's The System of Mineralogy, V. III: Silica minerals: New York, John Wiley & Sons, 334 p.

Griggs, D. T., 1967, Hydrolytic weakening of quartz and other silicates: Geophys. Jour. Royal Astronomical Soc., v. 14, p. 19-31.

Griggs, D. T., and Blacic, J. D., 1964, The strength of quartz in the ductile regime [abs.]: Am. Geophys. Union Trans., v. 45, p. 102-103.

——— 1965, Quartz: anomalous weakness of synthetic crystals: Science, v. 147, p. 292-295.

Heard, H. C., ms., 1962, The effect of large changes in strain rate in the experimental deformation of rocks: Ph.D. dissert., Univ. California, Los Angeles, Los Angeles, Calif., 202 p.

Heard, H. C., and Carter, N. L., 1968, Experimentally induced "natural" intragranular flow in quartz and quartzite: Am. Jour. Sci., v. 266, p. 1-42.

McLaren, A. C., and Retchford, J. A., 1969, Transmission electron microscope study of the dislocations in plastically deformed synthetic quartz: Physics Status Solidi, v. 33, p. 657-668.

McLaren, A. C., Retchford, J. A., Griggs, D. T., and Christie, J. M., 1967, Transmission electron microscope study of Brazil twin and dislocations experimentally produced in natural quartz: Physics Status Solidi, v. 19, p. 631-644.

Newkirk, H. W., and Smith, D. K., 1965, Studies on the formation of crystalline synthetic bromellite. Pt. 2, Macrocrystals: Am. Mineralogist, v. 50, p. 44-72.

Preston, John, 1958, Quartz lamellae in some Finnish quartzites: Comm. géol. Finlande Bull., n. 180, p. 65-78.

Sherby, O. D., and Burke, P. M., 1968, Mechanical behavior of crystalline solids at elevated temperature: Prog. in Math. Sci., v. 13, p. 324-379.

Sylvester, A. G., 1969, A microfabric study of calcite, dolomite and quartz around Papoose Flat Pluton, Calif.: Geol. Soc. America Bull., v. 80, p. 1311-1328.

Tullis, J., 1970, Quartz: preferred orientation in rocks produced by Dauphiné twinning: Science, v. 168, p. 1342-1344.

Turner, F. J., 1948, Note on the tectonic significance of deformation lamellae in quartz and calcite: Am. Geophys. Univ. Trans., v. 29, p. 556-569.