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THE GENESIS OF PLAGIOCLASE TWINNING IN THE NONEWAUG GRANITE

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ABSTRACT

In Nonewaug plagioclase Manebach twinning formed earliest, albite and parallel-sided pericline twinning next, then wedge-shaped pericline twinning and last exsolved plagioclase twinning. Primary Manebach twinning characteristically is simple with equal sized lamellae, mirror image crystal form on either side of composition faces and consistent occurrence in large crystals. Secondary albite and pericline twinning characteristically occur ubiquitously with polysynthetic lamellae of uniform width. Secondary twinning shows no consistent association with rock deformation and interprets resulting from stresses initiated during structural adjustments, perhaps from a high-low inversion, in response to waning temperatures.

Albite and pericline twins are the only twin laws in exsolved plagioclase, probably originating more or less contemporaneous with exsolution although some albite twinning may be inherited. Characteristically indistinct composition faces in exsolved plagioclase twins may result from the necessity of breaking strong bonds in twinning ordered plagioclase.

Growth twinning is controlled primarily by rapid crystal growth induced by supersaturation and consequently its presence indicates rapid crystal growth and may explain differences in twinning laws observed in igneous compared to metamorphic rocks. Crystal growth theory is incompatible with a primary origin for pericline twinning except when the rhombic section approximates the (001) lattice plane.

INTRODUCTION

The Nonewaug granite is situated in the central portion of the Western Highlands of Connecticut near the southern end of the Green Mountain Plateau (Rodgers, *et al.*, 1956). Most of the granite occurs in the Woodbury quadrangle. The Nonewaug pluton is a discordant roughly elliptical body surrounded by the metasedimentary Hartland formation. The granite consists of essential plagioclase, microcline and quartz with accessory muscovite and subordinate biotite. Plagioclase and microcline, in widely variable proportions, are the most abundant minerals, followed by quartz.

Plagioclase is probably the most abundant mineral in the Nonewaug granite. It occurs as: 1) discrete subhedral crystals, 2) inclusions in microcline and 3) exsolution lamellae in microcline. Subhedral plagioclase crystals crystallize first in portions of the granite lacking large microcline crystals. Large microcline crystals are locally abundant and often contain plagioclase inclusions. All of the plagioclases are abundantly twinned.

The twinning characteristics of plagioclase in the Nonewaug granite

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were determined by the five axis universal stage method of Emmons and Gates (1939). In some instances plagioclase composition was confirmed by determining refractive indices using the double variation method of Emmons (1943). Thin sections studied were provided by Dr. R. M. Gates from samples collected while mapping the Litchfield and Woodbury quadrangles in Connecticut for the State Geological and Natural History Survey (1951, 1954).

Plagioclase in the Nonewaug granite is in the low structural state. Values of $2V_z$ and the position of twin composition face poles relative to optic axes were collected during routine orientation of twins by the five axis method. Both parameters are sensitive to, and indicative of, the structural state of plagioclase and when plotted indicate Nonewaug plagioclase is in or very near the low structural state.

Plagioclase $2V_z$ values plotted on J. R. Smith's (1958) curve reveal a spread of approximately 10 degrees for a given composition with the distribution being nearly symmetrical about the curve. Some of the scatter is undoubtedly experimental although the spread from a single thin section is smaller than that for the entire granite suggesting a real scatter not easily explained by experimental error. Crystal strain is often responsible for radically altering $2V$ in other minerals, quartz for example, and may frequently account for the scatter of $2V$ in plagioclase.

Twin composition face poles plotted on migration curves also have a spread, although rather small compared to that for $2V$, again with a distribution approximately symmetrical about the low-temperature curve. Imperfect orientation of composition faces and deviation of the faces from ideal orientation may account for part of the spread but again scatter from a single thin section is less than that of the entire granite suggesting some of the spread is other than experimental error. Starkey (in press) points out that the development of perfect twins in plagioclase requires displacements non-parallel to the glide line in addition to homogeneous displacement parallel to the glide line and may or may not be completely achieved during twin development. Imperfect plagioclase twinning would be expected to show a scatter when plotted on migration curves. In addition Vogel (personal communication) has found that granitic igneous rocks exhibit scatter among crystals which he interprets resulting from differences in ordering among crystals.

Albite, pericline and Manebach twinning, in order of decreasing abundance, are the only common plagioclase twins in the Nonewaug granite. Most plagioclase crystals are polysynthetically twinned according to a single twin law, but crystals twinned according to more than one twin law are common. Of 267 twins studied in the Nonewaug granite 182 (68 per cent) are albite twins. Pericline twinning, of three distinct varieties, is second in abundance (16 per cent) and Manebach twinning is third (7 per cent). Relative age determinations and a listing of characteristic petrographic features was only possible for these more abundant twin laws. Other twin laws, of minor abundance in the granite, include albite-Ala B, Carlsbad, Ala A, Acline and Baveno twins. Only albite and pericline twins were identified in perthitic plagioclase lamellae and albite twinning is several times more abundant than pericline twinning.

Genesis of Plagioclase Twinning in the Nonewaug Granite

General Statement. In the Nonewaug granite, Manebach twins are interpreted as primary twins whereas albite and pericline twins are interpreted as secondary deformation twins. Albite, pericline and Manebach twins each have distinctive petrographic features which, along with their age relationships, suggest distinct modes of origin. Manebach twinning formed first. It displays many characteristics which indicate it is primary twinning. Albite and pericline twinning, which formed later than Manebach twinning, exhibit characteristics which indicate they are secondary deformation twins. Although most of the albite and pericline twins in perthitic plagioclase lamellae evidently originated during or shortly after exsolution, some albite twinning may be inherited from the microcline host.

Age Relationships of Plagioclase Twinning. The sequence of plagioclase twinning in the Nonewaug granite is, from earliest to latest: 1) Manebach twinning, 2) albite and parallel-sided pericline twinning (formed synchronously), 3) two wedge-shaped pericline twins and 4) twinning in perthitic plagioclase lamellae. This chronology is based on petrographic features and relative displacements between twins. Common association of the three twin laws facilitates determination of age relationships.

Manebach twinning is the earliest formed twin in the Nonewaug granite. It does not displace and is not displaced by associated albite and pericline twinning. However, whereas the distribution of albite and pericline twins is strongly influenced by associated Manebach twinning, the distribution of Manebach twinning is not influenced by associated twins. Albite and pericline twinning normally have a strongly asymmetrical distribution in adjacent Manebach twin individuals. Less typically the impact of later albite twinning on existing Manebach twinning has produced uniform albite lamellae in both Manebach individuals. Plagioclase crystals which show a combination of Manebach, albite and pericline twinning are locally abundant in the granite.

Albite twinning formed next in the granite. It is older than wedge-shaped pericline twins, younger than Manebach twinning and the same age as parallel-sided pericline twinning, which it alternately displaces and is displaced by and to which it is petrographically similar.

Three generations of pericline twinning occur in the Nonewaug granite. They are, from earliest to latest or from higher to lower structural states: 1) parallel-sided variety, 2) two wedge-shaped varieties and 3) twinning in perthitic plagioclase lamellae. Composition face pole plots of the peri-

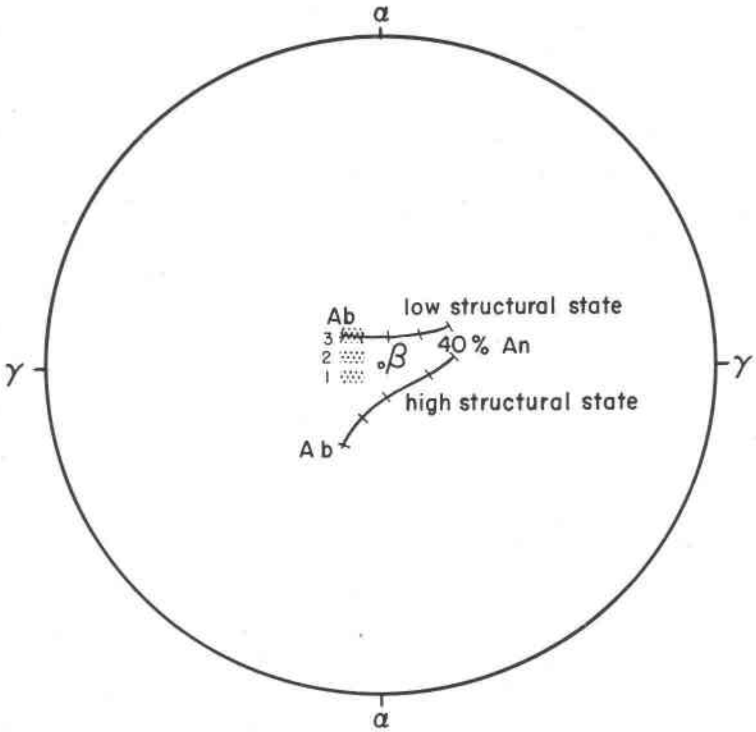


FIG. 1. Composition face pole plots of the 1) parallel-sided pericline twins, 2) wedge-shaped pericline twins and 3) pericline twins in exsolved plagioclase. Curves after J. V. Smith (1958).

cline twins on Smith's (1958) curves (Fig. 1) confirm petrographic evidence indicating three generations of pericline twinning. The parallel-sided pericline twinning formed earliest. Its face pole plots reveal an intermediate structural state approximately midway between the highest and lowest structural states. The two types of wedge-shaped pericline twinning formed later, in a lower structural state. Pericline twinning in perthitic plagioclase lamellae formed last in the lowest structural state.

Parallel-sided pericline twinning formed previous to wedge-shaped pericline twinning and synchronously with albite twinning which it alternately displaces and is displaced by. Since albite twinning is displaced by wedge-shaped pericline twinning it follows that both albite twinning and parallel-sided pericline twinning formed earlier than wedge-shaped pericline twinning. This relationship is verified by composition face pole plots since the other pericline twins lie closer to the lowest structural state than the parallel-sided variety indicating they formed later when plagioclase was more ordered. Face pole plots of parallel-sided pericline twinning lie about midway between Smith's highest and lowest structural curves.

Wedge-shaped pericline twins are the youngest of the common twins in discrete plagioclase crystals. They are of two petrographically distinct varieties: 1) a jagged variety and 2) a variety adjacent to Manebach composition faces. Besides being petrographically distinct these varieties have noticeably different, although over-lapping, face pole plots. These plots indicate that the jagged variety formed more recently, when the plagioclase was in a slightly lower structural state. However, face pole plots also indicate that both twin varieties formed when plagioclase was very close to the lowest structural state.

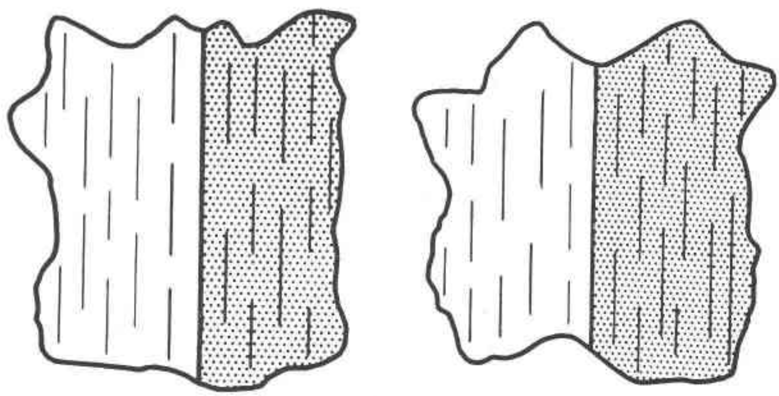
The jagged variety appears to have been formed by stresses transmitted in an essentially solid granite. The two outstanding characteristics of this twin—the jagged needle-like terminations and the en echelon pattern sometimes observed at high magnification—both imply such a condition as does the consistent association of this twin with other features of rock deformation. A partially fluid rock would not transmit stresses over the distance, a minimum of several crystal diameters, necessary to explain these features. Consequently, it must be assumed that the Nonewaug granite was essentially solid when this twin formed.

The twin variety adjacent to Manebach composition faces formed just previous to the jagged twin. It also has a wedge shape, but is not jagged, en echelon or associated with other rock deformation features. Therefore it probably formed before the granite had completely solidified but may have formed as late as the final stage of crystallization.

Thus, the twinning sequence is, from earliest to latest: Manebach twinning, albite and parallel-sided pericline twinning (formed synchronously) and wedge-shaped pericline twinning. Manebach, albite and parallel-sided pericline twinning probably formed during crystallization. The variety of wedge-shaped pericline twinning found adjacent to Manebach twinning formed later, perhaps as crystallization was ceasing, and the jagged wedge-shaped pericline twinning formed after the granite was essentially solid.

Twinning in exsolved plagioclase formed later than twinning in discrete plagioclase crystals. Composition face pole plots of pericline lamellae lie on Smith's lowest structural state curve. Pole plots of pericline twinning in discrete plagioclase crystals lie closer to the highest structural state indicating they formed earlier. Albite and pericline twinning in perthitic plagioclase probably formed essentially synchronously.

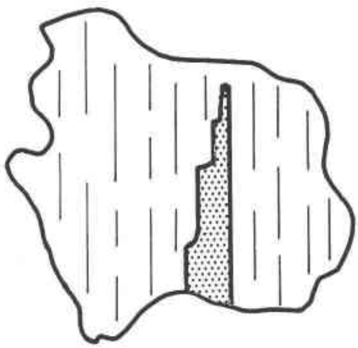
Primary Twinning. Manebach twinning in the Nonewaug granite is interpreted as primary twinning on the basis of its unique petrographic features. Support for this interpretation is drawn from the literature. Manebach twinning exhibits several unique characteristics. It is character-



FIGS. 2,3. Drawings perpendicular to (001). Two plagioclase crystals roughly divided into two equal parts by Manebach twinning. Notice that the crystal morphology developed in a complex mirror image pattern on either side of Manebach twinning (top of drawing). The (001) cleavage traces visibly parallel the Manebach composition faces.

istically simple twinning with lamellae of approximately equal width, although three lamellae were observed in two instances. Observations also show that plagioclase crystals containing Manebach twinning are usually larger than average with the greatest size difference in the (001) direction parallel to the Manebach composition face. Occasionally large steps were observed along Manebach composition faces, either singly or in opposed pairs. Also, some Manebach twins were observed to terminate within the crystal. In these instances the twins have one planar composition face parallel to the (001) cleavage and one non-planar composition face with an irregular shape, causing lamellae width to vary in an irregular manner. Another unique characteristic is the complex mirror image form exhibited by euhedral plagioclase crystals on either side of simple Manebach composition faces. None of these features were observed in the other common plagioclase twins.

The complex mirror image form displayed by more euhedral plagioclases on either side of Manebach composition faces suggests a primary origin for Manebach twinning. This relationship may be observed on the top of Figs. 2 and 3. The complex mirror image crystal form developed on either side of Manebach composition faces may easily be explained resulting from crystal growth across a twinned crystal, but is not likely to form after growth is essentially complete by twinning. Consequently,



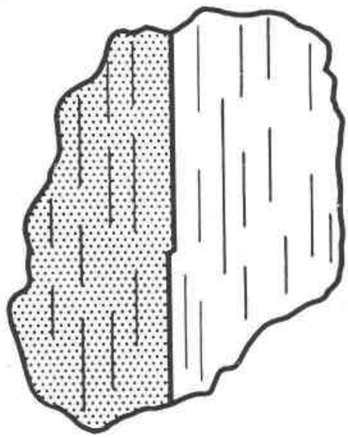


FIG. 4. Drawing perpendicular to (001). A Manebach twin lamella not extending entirely across the crystal, but instead terminating within the plagioclase crystal. Notice that the lamellae has one composition face planar and parallel to (001) and one composition face nonplanar and irregular in shape.

FIG. 5. Drawing perpendicular to (001). A plagioclase crystal divided into two roughly equal parts by simple Manebach twinning. Notice the large step along the otherwise planar Manebach composition face. The (001) cleavage visibly parallels the Manebach composition face.

Manebach twinning has influenced growth of the crystal and therefore was present during crystal growth which is only possible if Manebach twinning is primary twinning. Similar evidence for growth twinning is presented by Baker (1949) in diagram 5c on p. 256 of his paper.

Manebach twinning sometimes terminates within a crystal typically displaying an irregular shape difficult to form by shearing stresses. Usually these twins have one planar composition face parallel to the (001) cleavage and one non-planar composition face with an irregular shape (Fig. 4). Wedge shaped pericline twinning also terminates within plagioclase crystals, but have a sharp wedge shape readily explained by shearing stresses. It is difficult to imagine irregular shear planes with the shape of the Manebach twin lamellae. Primary twins terminating within crystals were commonly produced by Bolling *et al.* (1956) and Billig (1954) in laboratory crystal growth experiments.

The consistent occurrence of Manebach twinning in large plagioclase crystals implies a genetic relationship between the two and suggests a primary origin for Manebach twinning. Manebach twinning typically occurs in larger than average plagioclase crystals and differences in size may be considerable. These crystals are generally longest, and have their greatest size difference, parallel to the (001) composition face of Manebach twinning. The consistent occurrence of Manebach twinning in large plagioclase crystals implies that the twinning has influenced the rate of crystal growth and therefore was present during crystal growth. Hartman (1956), Frank (1958) and Price (1959) each indicate that crystals containing growth twinning grow faster than crystals without growth twinning. This occurs because the rate of crystal growth is enhanced at the re-entrant angle between twin lamellae compared to the normal edges of a crystal. Consequently, crystals with growth twins have a higher rate of crystal growth and are larger, especially parallel to the twinning composition face, than crystals without growth twins.

Large steps occasionally occurring along Manebach composition faces are interpretated as relict crystal growth features. Large steps occasionally occur along Manebach composition faces either singly (Fig. 5) or in opposed pairs causing Manebach twin lamellae to change width abruptly. These steps are readily visible at low magnifications and are approximately normal to Manebach composition faces. The steps may be relict features of crystal growth. Crystal growth proceeds by the creation and subsequent lateral motion of steps on a crystal surface with the steps seldom being uniformily spaced and monomolecular, but instead having a random spacing and various heights. In special cases extra large steps occur and may even be large enough to be visible without the aid of a microscope. Cabrera (1953) explains these large steps as the stable form energetically when twinning planes and related phenomena occur during crystal growth with a certain minimum supersaturation. It is conceivable that once these large steps form they might be stopped and persist throughout crystallization along composition faces of growth twinning as relict growth features. This may be the explanation for large steps observed along Manebach composition faces. These steps were not observed along composition faces of the other common twins.

Growth twinning in unzoned plagioclase should be simple in habit with lamellae of approximately equal size. Strong supersaturation and the resultant high rate of crystal growth may only occur once in the physiochemical environment of an intrusive rock; at the time of initial crystal nucleation. If so, then primary growth twinning has but one good opportunity to form and should be dominantly simple twinning with lamellae of nearly equal width. However, if recurrent supersaturation occurs, polysynthetic growth twinning might be formed. Bolling *et al.* (1956) formed polysynthetic growth twinning under controlled laboratory conditions by maintaining high levels of supersaturation. However, appreciable supersaturations subsequent to initial crystal nucleation would be expected to produce zoning in a solid solution mineral such as plagioclase. Consequently an absence or paucity of zoned plagioclase crystals indicates an absence of appreciable recurrent supersaturation during crystallization and any primary twinning present should be dominantly simple twinning with lamellae of nearly equal width.

The paucity of zoning in Nonewaug plagioclase indicates that any primary twinning present should be dominantly simple twinning with approximately equal sized lamellae just as is Manebach twinning. Plagioclase crystals in the Nonewaug granite are seldom zoned and the few zoned crystals consist of only two zones separated by indistinct boundaries. This paucity of zoning implies a lack of sufficient recurrent supersaturation to initiate multiple growth twinning. Therefore primary twinning in the Nonewaug granite should be dominantly simple with lamellae of approximately equal width. Accordingly, Manebach twinning is th only common twin likely to be primary.

The characteristics of Manebach twinning in the Nonewaug granite are readily explained by crystal growth, but are difficult to explain by shearing stresses. Despite the lack of agreement on even one conclusive feature for identifying primary twinning, Vance (1961) reviews the lack of evidence, the combination of petrographic features displayed by Manebach twinning is believed to indicate a primary origin. Two characteristics, the relationship between euhedral plagioclase crystal form and Manebach twinning and the selective occurrence of Manebach twins in large crystals, each offer strong evidence for a primary origin. The difficulty of explaining many of the Manebach twin characteristics by shearing stresses also offers negative evidence for a primary origin.

Only one Manebach twin was observed in plagioclase included by microcline. This appears anomalous, since Manebach twinning, if it is growth twinning, would have formed previous to inclusion of plagioclase and might be expected to be common in included plagioclase. This paradoxical situation may be resolved by noting the infrequency of Manebach twins in portions of the granite containing large microcline crystals. The absence of Manebach twinning near microcline may be a result of plagioclase not being the first mineral crystallized thereby reducing, if not eliminating, supersaturation during its crystallization. Also Manebach twinned plagioclase crystals are larger and therefore less likely to become included in microcline.

Secondary Twinning. Albite twinning in the Nonewaug granite is regarded as secondary deformation[1] twinning on the basis of its petrographic features and age relationships. Albite twinning is characterized by several features of which two, ubiquity of occurrence and fine polysynthetic lamellae of equal width, offer evidence for a secondary origin. The most characteristic feature of albite twinning is its nearly ubiquitous occurrence. It is more abundant than all other twin laws totaled, comprising 68 per cent of the twinning observed. Although it frequently occurs alone, other twin laws are nearly always accompanied by albite twinning. Albite twins characteristically extend entirely across the crystal forming narrow parallel-sided lamellae of constant width that are rarely altered. Also albite twinning was occasionally observed to display a regularity of fine lamellae not observed in other twins. No consistent association was observed between albite twinning and other deformation features in the granite. Two of these characteristics, ubiquity of occurrence and occasional presence of fine polysynthetic lamellae of equal width, suggest a secondary origin for albite twinning.

The occurrence of fine polysynthetic albite lamellae of regular width is in complete discord with a primary origin but is easily explained by a secondary origin. Albite twinning in the granite sometimes displays a unique regularity of fine polysynthetic lamellae. As discussed previously, primary twinning in the Nonewaug granite should be simple in habit. However, even allowing for the possibility of polysynthetic growth twinning, the occurrence of numerous fine lamellae of regular width is, as Vance (1961) points out, in complete discord with the process of growth twinning. The probability that primary lamellae would be nucleated simultaneously on both sides of a growing crystal rhythmically, as is required to explain these lamellae, is exceedingly low. However, these fine polysynthetic lamellae of regular width are easily explained as secondary deformation twinning. This is perhaps the strongest single line of evidence for a secondary origin for albite twinning.

The near ubiquity and lack of association of albite twinning with other deformation features in the granite may be explained as forming from stresses initiated by structural adjustments during a high-low plagioclase inversion. Plagioclase in the Nonewaug granite probably crystallized above the transformation temperature, approximately 700° for albite (Tuttle and Bown, 1950), in the high-temperature form and cooled slowly

[1] Also called glide or mechanical twinning.

allowing inversion to the low-temperature form. Turner (1951) states that temperature may exert an important influence on twinning and that most magmatic crystallization must take place above the inversion temperature and most, if not all, metamorphic processes must be governed by temperatures considerably below the transformation temperature. If the plagioclase crystallized above the transformation temperature and inverted, stresses initiated during this inversion would be experienced by every plagioclase crystal in the Nonewaug granite. Tuttle and Bowen's article (1950) mentions that this inversion has a large heat of transformation, approximately 9 cal/gm for albite, suggesting marked structural changes. The stresses induced by this transformation would provide a nearly ubiquitous initiating mechanism for albite twinning. Both the high- and low-temperature plagioclase forms in the Nonewaug granite were apparently triclinic since no evidence was observed for the monoclinic form (Brown, 1960). Consequently twins formed by stresses arising during the high-temperature triclinic to low-temperature triclinic transformation are deformation twins and not transformation twins since by definition a lowering of crystal symmetry and the consequent suppression of symmetry elements during a transformation is required to produce transformation twinning. Tuttle and Bowen (1950) observed that twinning was produced during the low-high transformation in an albite studied. However, it is also possible that the Nonewaug granite had a sufficiently high mineralizer content to reduce the temperature of crystallization below the transformation temperature, thereby avoiding the transformation and crystallizating in an intermediate structural form. Nevertheless the structural adjustments necessary to reach the present low structural state may have initiated stresses sufficient to cause secondary twinning.

If albite twinning in the Nonewaug granite is accepted as secondary twinning, then it is necessary also to accept all of the pericline twinning as secondary since it formed after the albite twinning.

Two distinct varieties of pericline twinning occur in the Nonewaug granite and both are interpreted as secondary deformation twins. The two varieties are: 1) parallel-sided pericline twinning and 2) wedge-shaped pericline twinning. The wedge-shaped variety may be further subdivided, on the basis of petrographic features, into two varieties: 1) twinning adjacent to Manebach composition faces and 2) jagged twinning. The petrographic features and age relationships of pericline twinning indicate it is deformation twinning.

Parallel-sided pericline twinning is petrographically similar to albite twinning. As in albite twinning the composition faces seldom show alteration and usually extend entirely across crystals with a constant width.

Also, no consistent association was observed between this pericline twinning and other deformation features in the granite. However, it is less abundant and never displays the regularity of fine lamellae displayed by albite twinning.

The parallel-sided pericline twinning formed in a manner similar to albite twinning although its requirement for a greater resolved shearing stress has resulted in a lesser abundance. The similar characteristics and synchrony of formation suggest this twinning formed in essentially the same manner as the albite twinning. Borg, Handin and Higgs (1959) have explained the lesser abundance of pericline twinning in their experiments deforming jacketed plagioclase (An_{67}) crystals at 400° C. Experiments were performed dry at five kilobars with a constant strain rate of one per cent per minute with uniaxial compression applied in two different orientations, both inclined 45° to (010) in a plane quasi-normal to the *a* axis. Although they expressed some uncertainty over the extent to which twinning was produced, they concluded that the strength anisotropy suggested that critical resolved shear stresses for albite twinning are only about half that for pericline twinning. Thus pericline twinning would be expected to be less abundant than albite twinning when produced by the same stresses.

One variety of wedge-shaped pericline twinning occurs adjacent to high energy Manebach composition faces which served as loci for its development. This twinning usually occurs along small portions of most Manebach composition faces and occasionally extends along the entire face, but only rarely it is developed beyond composition faces along crystal boundaries or inclusions. Normally the pericline twinning terminates a short distance from Manebach composition faces although it sometimes extends to crystal boundaries. This twinning is usually polysynthetically developed on both sides of Manebach composition faces in at least partial mirror images (Fig. 6). Generally these pericline lamellae are quite small, but occasionally they attain a large size. In some instances a semi-parallel orientation was observed among the lamellae. The high energy of the Manebach composition face has apparently caused it to serve as a loci for the development of the secondary pericline twinning under stress.

The semi-parallel orientation of these pericline twin lamellae probably resulted from differences in the extent of plagioclase ordering when the lamellae formed. Mugge (1930) and Smith (1958) have pointed out that the position of the rhombic section is dependent on structural state as well as composition of plagioclase. Structural state is mainly a function of temperature and its rate of change. Therefore, the semi-parallel orientation of pericline twin lamellae may be due to having formed at different times during a period of diminishing temperatures. If so, the angle of misalignment between twin lamellae would be a function of differences in ordering at the time of formation of the various lamellae.

The jagged variety of wedge-shaped pericline twinning has many unique characteristics. The most obvious of these are jagged edges and discontinuous en echelon lamellae sometimes observed at high magnifications. Another distinct characteristic is abundant sericitization observed

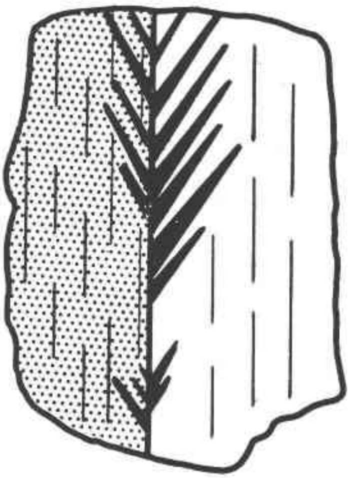


FIG. 6. Drawing parallel to (010). Small semi-parallel, wedge-shaped pericline twinning developed along the Manebach composition face in plagioclase. Notice that pericline twinning exhibits a partial mirror image effect across the Manebach composition face at one end. Also notice that pericline twinning usually extends only a short distance from the composition face. The (001) cleavage visibly parallels the Manebach composition face.

FIG. 7. Drawing perpendicular to (010). A small patch of exsolved plagioclase surrounded by its microcline host. Notice that albite twinning (black) may be traced continuously from microcline across plagioclase and back into microcline.

along composition faces whereas alteration is scarce in other twin lamellae. Also this twin often pinched out in a series of needle-like lamellae. However, the consistent association of this twin with other deformation features in the granite such as bent and broken crystals is probably the most distinctive characteristic. None of these characteristics were observed in other common twins.

Petrographic characteristics of jagged pericline twinning indicates it formed in a solid rock by stresses acting over a minimum of several crystal diameters. The two most obvious characteristics of this twin, jagged edges and en echelon pattern, suggest shearing stresses operating in a confined space. The consistent association of this twin with other rock deformation features implies a common origin and indicates that the granite must have been essentially solid in order to transmit stresses over the required several crystal diameters to produce this association. Since stresses caused by structural adjustments within a crystal would probably not be effective in deforming surrounding crystals, other forces must be responsible for forming the jagged pericline twinning.

Perhaps differences in secondary twin lamellae in Nonewaug plagioclase can be attributed to formation at different states of order-disorder. Secondary twin lamellae in the Nonewaug granite plagioclase may be divided into two geometrically distinct groups; parallel-sided lamellae and wedge-shaped lamellae. It may be hypothesized that since the earlier parallel-sided twinning formed at high temperatures while plagioclase was relatively disordered it allowed twinning readily without breaking strong bonds resulting in parallel-sided lamellae. Subsequently wedge-shaped twinning formed at lower temperatures in a more ordered state may have needed to break strong bonds to twin resulting in wedge-shaped lamellae. Despite the lack of any direct evidence for this hypothesis it presents a plausible explanation for the two different secondary twin lamellae shapes in the Nonewaug granite.

Only albite and pericline twins were identified in perthitic plagioclase and most of the twinning originated during or shortly after exsolution although some albite twinning may be inherited from the microcline host. Perhaps the exsolved plagioclase has a structural preference for albite and pericline twins since they are the only twin laws found in the abundantly twinned exsolved plagioclase. Although some of the albite twinning may be inherited from the microcline host most albite twinning and all pericline twinning probably formed from internal stresses originating more or less contemporaneous with exsolution. Composition face pole plots of this pericline twinning on Smith's curves indicate it formed later then all pericline twins in discrete plagioclase crystals since its pole plots lie on the lowest structural state curve. It is logical to assume that albite and pericline twinning in perthitic plagioclase formed essentially synchronously.

Albite and pericline twinning in perthitic plagioclase lamellae exhibit characteristics quite distinct from twinning in discrete plagioclase crystals. Most exsolved plagioclase is abundantly twinned with individual twin lamellae varying considerably in width and shape across the exsolved plagioclase. In some instances albite twinning may be traced continuously from microcline across exsolved plagioclase and back into microcline (Fig. 7). Usually, however, albite twin lamellae in exsolved plagioclase appear to have no continuation in microcline. Albite twinning is much more abundant than pericline twinning and again the greater ease of albite twinning probably was an influencing factor.

Indistinct composition faces typical of much albite and pericline twinning in exsolved plagioclase may be due to the necessity of breaking strong bonds to twin plagioclase in the lowest structural state. Twinning composition faces range from sharp to vague and indistinct with pericline composition faces usually more vague and indistinct than associated albite composition faces. These indistinct composition faces are often not resolvable even at high magnifications. Furthermore, face pole plots of pericline twinning on Smith's curves (Fig. 1) indicates formation while plagioclase was in the lowest structural state. Smith (1962) pointed out that twinning formed in the low structural state may be irregular and patchy because of the necessity of breaking strong bonds in order to accomplish twinning (Laves, 1952). Consequently, it seems possible that the necessity of breaking strong bonds to twin ordered plagioclase may be responsible for causing indistinct twin composition faces in exsolved plagioclase.

Albite and pericline twinning are the only twins observed in the abundantly twinned exsolved plagioclase. MacKenzie and Smith (1955, 1956) and Smith and MacKenzie (1958, 1959) conducted a series of investigations on alkali feldspars and mention only albite and pericline twins in the perthitic plagioclase. It would thus appear that exsolved plagioclase has a structural preference for albite and pericline twin laws since they occur abundantly to the exclusion of all other twin laws. Secondary albite and pericline twins were probably initiated by stresses relating to differences in lattice geometry between exsolved plagioclase and its microcline host. However, some albite twinning is continuous from microcline across exsolved plagioclase and back into microcline and therefore may be inherited from the microcline host. It is not possible for pericline twinning to be inherited in this manner since the rhombic section differs in orientation by approximately 90° from microcline to plagioclase. In microcline the rhombic section is nearly coincident with the (100) pinacoid while in plagioclase it approximates the (001) pinacoid.

Petrogenic Significance of Plagioclase Twinning

General Statement. Plagioclase twinning develops in response to the physicochemical environment which varies with time and is controlled primarily by temperature, pressure and chemical composition. Twinning may be either primary or secondary. Primary twins originate during crystal growth and are called growth twins whereas the three mechanisms of secondary twin origin are deformation twinning, agglutination twinning and transformation twinning. Consideration of each mechanism of twin origin relative to the physicochemical rock forming environment indicates certain twin origins should be restricted to certain environments. Furthermore these results may be correlated with twin law distribution to show that certain twin laws are usually confined to a specific origin.

Plagioclase composition has been eliminated as a possible variable in effecting twin formation in this study by confining investigation to a single rock unit. However, to date, no cogent evidence has been presented in the literature to indicate that plagioclase composition per se should influence the distribution of plagioclase twinning laws. If any correlation between plagioclase composition and distribution of twin laws exists, it appears probable to the author that it is probably either fortuitous or due to differences such as environment, crystal morphology or order-disorder which may vary systematically to some extent with composition. Chapman (1936) found no differences in twin laws developed in plagioclases of different composition in a differentiated sill.

Primary Twinning. Growth twins form when newly added atoms on a growing crystal face become attached in a twinned orientation relative to the established portion of the crystal. Buerger (1945) indicated that growth twins form as a result of an accident of the crystal growth process. He postulated that the first atom or cluster of atoms to be received on a growing crystal face may assume a coordination position different from the normal lattice pattern already established. These new atoms assuming a different orientation will have an approximation to minimum energy since they have the same nearest neighbor coordination with only more distant coordinations differing. A position only approximating minimum energy will not be as stable as a position of minimum energy and under normal rates of crystal growth the atoms will tend to be displaced or reoriented. As the rate of crystal growth increases the probability that these atoms will remain in the new orientation increases since more atoms or clusters of atoms rapidly arrive and assume similar orientation. Conditions are most propitious for the formation of growth twins during the initial stage of crystal growth when the rate of crystal growth is at a maximum and essentially only nearest neighbor forces are effective.

Crystal growth proceeds at a leisurely rate at saturations below supersaturation compared to growth rates under conditions of supersaturation. Furthermore spontaneous crystallization will not occur until a certain critical value of supersaturation is attained. Ostwald, Miers and others (Buckley, 1951) conducted experiments on a variety of substances showing that the critical value of supersaturation lies on a supersolubility curve unique for each composition and separated from the solubility curve by a metastable region (Fig. 8). In the metastable region small crystals are constantly nucleating but are sufficiently small that their solubility exceeds that of the supersaturated solution and they redissolve. Increases in supersaturation result in larger crystals due to increases in the rate of nucleation and consequent increases in rate of nuclei collisions until the supersolubility curve is reached. At this critical value crystals grow rapidly enough to attain the minimum size necessary to adequately lower their solubility to prevent dissolvement. These crystals will continue to grow very rapidly until concentration reduces to saturation. Thus supersaturation normally reaches its acme

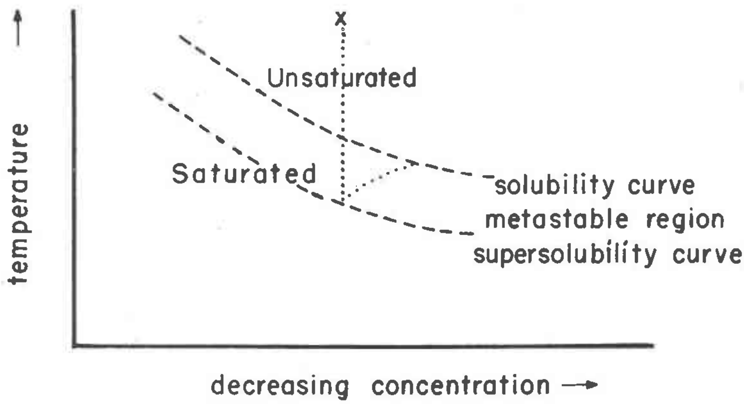


FIG. 8.

just previous to initial nucleation and ceases shortly after nucleation commences. However, abrupt pressure, temperature or chemical changes in a system may result in premature crystal nucleation.

Crystal growth experiments on ionic compounds by Johnson and Deicha (Cahn, 1954), covalent germanium by Bolling *et al.* (1956) and metallic cadmium by Price (1959) cover the gamut of important inorganic bond types and indicate that bonding characteristics are of secondary importance as compared to a high rate of crystal growth in forming growth twins.

Solid impurities in a system generally reduce supersaturation and for a given supersaturation the rate of crystal growth. The freer a system is of solid particles of any sort, the greater the probability of supercooling (Buckley, 1951). If, despite the presence of solid impurities, some supersaturation is achieved, the rate of crystal growth will probably be less than if solid impurities were absent. The rate of crystal growth is often radically altered by impurities, the usual effect is to reduce the growth rate for a given supersaturation (Cabrera and Vermilyea, 1958). Thus supersaturation and consequent high growth rates would not be expected in systems containing appreciable amounts of solid impurities.

Primary twinning in the Nonewaug granite is characterized by petrographic features distinct from those exhibited by secondary twinning. Experimental and theoretical work on primary twinning in the literature presents characteristics similar to those in plagioclases of the Nonewaug granite and consequently indicates these characteristics may have wide application for recognition of primary plagioclase twinning.

A list of criteria characterizing primary plagioclase twinning in the Nonewaug granite has been generalized to provide recognition of primary twinning as follows:

1) Primary twinning is usually simple with lamellae of equal width or less often, polysynthetic consisting of a few broad lamellae generally of unequal width.
2) Plagioclase crystals containing primary twinning are usually larger than plagioclase crystals without primary twins and size differences are sometimes considerable. The largest difference in dimensions is normally parallel to the primary twinning composition face.
3) Large steps may occur along primary twin composition faces either singly, in opposed pairs or in other combinations causing abrupt and irregular changes in lamellae width always independently of each other and deformation in the crystal.
4) Primary twinning does not always extend entirely across a crystal, and in these cases may have irregular lamellae shapes not easily envisioned as shear planes.
5) Euhedral plagioclase crystal form (or zoning) show mirror image relationships, sometimes complex, on either side of primary twinning composition faces. Zoning will be deflected, but continuous, across primary twinning.
6) Primary twinning forms earlier than associated secondary twinning.

The presence of growth twinning indicates rapid rates of crystal growth and may explain many of the differences in twinning laws observed in igneous compared to metamorphic rocks. It is well known that certain twin laws are much more abundant in igneous rocks than in metamorphic rocks. Turner (1951), among others, agrees that it is possible that twinning behavior is effected differently by metamorphic crystallization in an essentially solid medium and by magmatic crystallization in a liquid medium. Since growth twinning requires a high rate of crystal growth induced by supersaturation and supersaturation is not likely in a system containing solid impurities, growth twinning is unlikely in metamorphic rocks. On the other hand supersaturation and growth twinning should be readily possible in an igneous environment. Accordingly it seems probable that certain twin laws distinctive of igneous plagioclase are primary and that the recognition of primary twinning may be a useful criterion of igneous origin.

The prevalence of simple albite twins in low grade schists thought to be primary twins by Turner (1951) presents an enigma in that it appears difficult to account for the high rate of crystal growth believed necessary for the formation of growth twins in these rocks.

A literature survey indicates that dominantly simple plagioclase twins, such as Manebach, Baveno and Carlsbad twins, are essentially confined to igneous rocks. Gorai (1950) believes that Manebach, Baveno and Carlsbad twins are essentially confined to igneous rocks and are rare. He also notes no marked differences between the twinning in phenocrysts and groundmass plagioclase in volcanics studied except that the phenocrysts are richer in pericline twinning and the less common twins such as Manebach twins. This is precisely the distribution to be expected of Manebach twinning if it is growth twinning. On the other hand, Suwa (1956) studied plagioclase twinning in metamorphic rocks, granites and volcanic rocks from Japan and arrived at opposite conclusions. He classified Manebach and Baveno twins as being characteristic of metamorphic rocks. Phillips (1930), Turner (1951), Engel and Engel (1960) and nearly all other authors are in basic discord with Suwa and believe that metamorphic plagioclases twin dominantly on the albite and pericline laws, with even pericline twins being scarce at lower grades of metamorphism. Thus a resume of the literature indicates that dominantly simple plagioclase twins, such as Manebach, Carlsbad and Baveno twins, occur almost exclusively in igneous rocks. Consequently, distribution of dominantly simple plagioclase twins is that expected if they are primary twins. However, Vance (1961) believes that most Carlsbad twins are agglutination (synneusis) twins. Such an origin would also be in agreement with their limited distribution. Simple Carlsbad and Baveno twinning observed by the author in plagioclase and potash feldspar of other igneous rock units sometimes exhibit large steps along composition faces similar to those displayed by Manebach twinning in the Nonewaug granite suggesting, in these cases, a primary origin. It appears likely, since a solid solution mineral such as plagioclase is sensitive to recurrent supersaturation by zoning, that if much primary polysynthetic twinning exists it will only be common in rocks with highly zoned plagioclase such as volcanic rocks. There is no reason that albite twinning can not, on occasion, be primary.

The nature of Baveno twin boundaries indicates that Baveno twinning should normally be primary. Cahn (1954) states that Baveno twins could readily form as growth twinning but are not likely to be deformation twinning. The structures fit together only after a relative displacement along the twin boundary forming a glide plane of symmetry. This is permissible, according to Cahn, for a growth twin, but would lead to severe stresses in the interface of a deformation twin.

The theory of crystal growth is incompatible with a primary origin for pericline twinning, which requires crystal growth along a non-lattice plane of the crystal, except when the rhombic section approximates the (001) basal pinacoid. Vance (1961) proposed that primary polysynthetic pericline twinning is common in igneous plagioclase. However, the rhombic section is a geometrical plane not parallel to any lattice plane of plagioclase except at the andesine composition, where it briefly parallels the (001) basal pinacoid. Crystal growth normally proceeds by the formation and subsequent lateral motion of steps along a lattice plane. It is hard to envision the process that would result in growth along a geometrical plane not parallel to any lattice plane of the crystal to form even a simple twin. The process, as pointed out by Cahn (1954), becomes unthinkable when polysynthetic pericline twinning is considered. However, secondary pericline twinning may be easily visualized. Nevertheless Vance (1962) presented evidence in a single crystal for primary origin of a simple pericline twin. This is possible since the twin lamellae originates in plagioclase of andesine composition and thus represents the special case where the rhombic section approximates the (001) basal pinacoid.

Secondary Twinning. Secondary twinning may be divided into deformation twinning, agglutination twinning and transformation twinning. Deformation twinning is probably far more abundant that the other two varieties in plagioclase.

Deformation twins form as a crystal yields to stress plastically by twin gliding. Each atom in a crystal is surrounded by energy barriers with directional variations in strength. Directions with the lowest energy barriers are most favorable to twinning and twins form if resolved shearing stresses sufficient to overcome the energy barrier are applied. If energy barriers prohibiting twinning are too great, the force of rupture may be necessary to cause gliding and twinning will not occur. For a given direction with relatively low energy barriers certain lattice planes may contain imperfections, especially dislocations, which further reduce resistance to twin gliding and make these planes more susceptible to twin gliding than other planes of the same orientation.

Cottrell and Bilby (1951) have explained the growth of deformation twinning through a finite thickness of crystal by the movement of a single imperfect dislocation. A major problem in explaining deformation twinning was developing twinning homogeneously through numerous successive lattice planes in contrast to the behavior of slip, where deformation concentrated on a single plane. In terms of dislocations homogeneous twinning shear requires either an avalanche of dislocations, at least one on every lattice plane without exception, or the motion of a single dislocation successively from one lattice plane to the next in a regular manner. Cottrell and Bilby show that a single imperfect dislocation can produce a monolayer of twinned crystal for each revolution that it completes and, at the same time, climbs up one lattice spacing to the next layer, where it repeats the process and in so doing builds up a thick lamella of twinned material. The usual elastic interactions will occur between dislocations and other imperfections in the crystal, with the final size and shape of the twinned portion of the crystal determined by its strain energy and by positions of large obstacles in the crystal. Once a large obstacle is encountered it may be easier to form new lamellae elsewhere than to overcome the obstacle. Therefore secondary deformation twinning will not necessarily be polysynthetic or have a regularity of twin lamellae, although polysynthetic twin lamellae of regular width are almost certainly secondary. The nature of the stresses required to cause twin gliding are not restricted by this mechanism.

Agglutination twins are formed when two or more essentially grown crystals make contact and adhere in a twinned orientation. Agglutination twins only form in environments allowing crystals some freedom of movement and such an environment must be at least partially fluid. Normally these twins might be expected to be more prevalent in an environment where the fluid has movement, such as normally occurs in an extrusive igneous environment. Hartman (1956) classified agglutination twinning as a special variety of growth twinning. However, the distinct appearance of agglutination twins, as illustrated by Ross (1957), who calls them combination twins, and their formation after crystal growth is essentially complete, indicates a need for a distinct category as secondary twins.

Transformation twins form in crystals as certain symmetry elements are suppressed during a phase transition in the solid state. Phase transformations occur as crystals thermodynamically assume the crystalline form represented by a minimum free energy in equilibrium with its environment, and may result from either temperature or pressure changes. Only temperature induced transformations are regarded as important in either metamorphic or igneous plagioclase. A crystal may or may not twin when it undergoes a phase transformation. According to Buerger (1945) when temperature reaches the transformation level transformation nuclei will proceed through the crystal at the speed of heat transmission. In any but the smallest crystals, transformation nuclei will occur spontaneously in various parts of the crystal and spread from these centers. Adjacent centers will meet in either a parallel or different orientation, with those in different orientation being twinned relative to each other.

Inasmuch as the high-low inversion of plagioclase occurs at temperatures above those normally attained by metamorphism, transformation twinning in plagioclase, if it exists, is probably restricted to igneous rocks.

Plagioclase deformation twinning may form in either an igneous or metamorphic environment although different twinning forces may be dominant in the two environments. The difficulty of twinning plagioclase in the ordered state (Laves, 1952) is probably the dominant factor in reducing the amount of deformation twinning in metamorphic rocks. Laves contends that deformation twinning is easily possible in the disordered state without breaking strong bonds while deformation twinning in the ordered state requires breaking of strong bonds and is associated with considerable local shifting of the Si/Al atoms, which is extremely sluggish. Since metamorphic plagioclase forms at relatively low temperatures, it will probably be approaching the ordered structural state, depending mainly on the temperature of metamorphism. On the other hand igneous plagioclases normally form at higher temperatures and would be in a more disordered state, thus being more susceptible to the development of deformation twinning. Deformation twinning probably accounts for most metamorphic plagioclase twinning since other genetic types are unlikely, and may also be responsible for most igneous plagioclase twinning. There is little room for doubt that at least some, and perhaps the large majority, of twinning so common in plagioclase is produced by plastic deformation in the solid state in response to external forces.

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References

Baker, G. (1949) Note on volcanic rocks with special reference to plagioclase feldspar from Mt. Bogana, Bougainville Island, Solomon Islands. *Trans. Am. Geophys. Union,* **30,** 250–262.

Billig, E. (1954) Growth twins in crystals of low coordination number. *Inst. Metals Jour.* **83,** 53–56.

BOLLING, C. F., W. A. TILLER AND J. W. RUTTER (1956) Growth twins in germanium. *Canad. Jour. Phys.* **34,** 234–240.

BORG, I., J. HANDIN, AND D. V. HIGGS (1959) Experimental deformation of plagioclase single crystals. *Jour. Geophys. Res.* **64,** 1094–1095.

BROWN, W. L. (1960) Lattice changes in heat treated plagioclases—The existence of monalbite at room temperature. *Zeit. Krist.* **113,** 297–329.

BUCKLEY, H. E. (1951) *Crystal Growth,* John Wiley & Sons, Inc., New York.

BUERGER, M. J. (1945) The genesis of twin crystals. *Am. Mineral.* **30,** 469–482.

CABRERA, N. (1953) Macroscopic spirals and the dislocation theory of crystal growth. *Jour. Chem. Phys.* **21,** 1111–1112.

——— AND D. A. VERMILYEA (1958) The growth of crystals from solution, from *Growth and Perfection of Crystals,* ed. by Doremus, Roberts and Turnbull, John Wiley & Sons, Inc., New York, 393–410.

CAHN, R. W. (1954) Twinned crystals. *Advances in Phys.* **3,** 363–445.

CHAPMAN, W. M. (1936) A study of feldspar twinning in a differentiated sill. *Am. Mineral.* **21,** 33–47.

COTTRELL, A. H. AND B. A. BILBY (1951) A mechanism for the growth of deformation twins in crystals. *Phil. Mag.* **42,** 573–581.

EMMONS, R. C. (1943) The universal stage. *Geol. Soc. Am. Memoir* **8.**

——— AND R. M. GATES (1939) New method for the determination of feldspar twins. *Am. Mineral.* **24,** 577–589.

ENGEL, A. E. J. AND C. G. ENGEL (1960) Progressive metamorphism and granitization of the major paragenesis, northwest Adirondack Mountains, New York, Part 2, Mineralogy, *Geol. Soc. Am. Bull.* **71,** 1–57.

FRANK, F. C. (1958) Introductory lecture, from, *Growth and Perfection of Crystals,* ed. by Doremus, Roberts and Turnbull, John Wiley & Sons Inc., New York, 3–10.

GATES, R. M. (1951) The bedrock geology of the Litchfield quadrangle, Connecticut. *Conn. Geol. Nat. Hist. Surv., Misc. Series* **3.**

——— (1954) The bedrock geology of the Woodbury quadrangle, Connecticut. *Conn. Geol. Nat. Hist. Surv., Quadr. Rept.* **3.**

——— AND P. E. SCHEERER (1963) The petrology of the Nonewaug granite, Connecticut. *Am. Mineral.* **48,** 1040–1069.

GORAI, M. (1950) Petrological studies on plagioclase twins. *Am. Mineral.* **36,** 884–901.

HARTMAN, P. (1956) On the morphology of growth twins. *Zeit. Krist.* **107,** 225–237.

LAVES, F. (1952) Mechanische Zwillingsbildung in Feldspaten in Abhangigkeit von Ordnung-Unordnung der Si/Al—Verteilung innerhalb des (Si, Al)$_4$O$_8$—Gerustes. *Naturwissenschaften,* **23,** 546–547.

MACKENZIE, W. S. AND J. V. SMITH (1955) The alkali feldspars, I, Orthoclase-micro-perthites. *Am. Mineral.* **40,** 707–732.

——— (1956) The alkali feldspars, III, An optical and *x*-ray study of high-temperature feldspars. *Am. Mineral.* **41,** 405–427.

MÜGGE, O. (1930) Über die Lage des rhombischen Schnitte im Anorthit und seine Benützung als geologisches Thermometer. *Zeit. Krist.* **75,** 337–344.

PHILLIPS, F. C. (1930) Some mineralogical and chemical changes induced by progressive metamorphism in the Green Bed group of the Scottish Dalradian. *Mineral. Mag.* **22,** 239–256.

PRICE, P. B. (1959) Twinning in cadmium dendrites. *Phil. Mag.* **4,** 1229–1241.

RODGERS, J., R. M. GATES, E. N. CAMERON AND R. J. ROSS (1956) Preliminary geological map of Connecticut, 1956. *Conn. Geol. Nat. Hist. Surv.*

Ross, J. V. (1957) Combination twinning in plagioclase feldspars. *Am. Jour. Sci.* **255,** 650–655.

Smith, J. R. (1958) The optical properties of heated plagioclases. *Am. Mineral.* **43,** 1179–1194.

Smith, J. V. (1958) The effect of composition and structural state on the rhombic section and pericline twins of plagioclase feldspar. *Mineral. Mag.* **31,** 914–928.

——— (1962) Genetic aspects of twinning in feldspars. *Norsk Geol. Tidssk.* **42,** 244–263.

——— and W. S. MacKenzie (1958) The alkali feldspars, IV, The cooling history of high-temperature sodium rich feldspars. *Am. Mineral.* **43,** 872–889.

——— and W. S. MacKenzie (1959) The alkali feldspars, V, The nature of orthoclase and microcline perthites and observations concerning the polymorphism of potassium feldspar. *Am. Mineral.* **44,** 1169–1186.

Starkey, J. (in press) Glide twinning in the plagioclase feldspars.

Suwa, K. (1956) Plagioclase twinning in Ryoke metamorphic rocks from the Mitsuemura area, Kii Peninsula, central Japan. *Jour. Earth Sci. Nagoya Univ.* **4,** 91–122.

Turner, F. J. (1951) Observations on twinning of plagioclase in metamorphic rocks. *Am. Mineral.* **36,** 581–589.

Tuttle, O. F. and Bowen, N. L. (1950) High temperature albite and contiguous feldspars. *Jour. Geol.* **58,** 572–584.

Vance, J. A. (1961) Polysynthetic twinning in plagioclase. *Am. Mineral.* **46,** 1097–1119.

——— (1962) Observations on the rhombic section of a zoned plagioclase crystal. *Mineral. Mag.* **33,** 125–131.

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