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POLYSYNTHETIC TWINNING IN PLAGIOCLASE

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ABSTRACT

Primary polysynthetic twinning in plagioclase, though much less common than secondary twinning, can be demonstrated by the relations between crystal morphology and primary twin lamellae in euhedrally zoned plagioclase. In twinned plagioclase grains cut normal to the *a*-axis and showing the (001) and (010) cleavages, both the zones and cleavages—(001) in albite twinning, (010) in pericline twinning—make a zigzag of about 8° as they cross the composition planes. The relations of truncated twin lamellae to crystal morphology in such *a*-normal sections indicates that the twinning is primary. The parallelism of zones and clevages further establishes that the plagioclases studied grew in essentially their present triclinic form and cannot have inverted from a hypothetical plagioclase of markedly higher symmetry. The twinning of these plagioclases therefore cannot be transformation twinning.

Contrary to a widely held view, it is not so much plagioclase composition and structure, but environmental conditions during crystal growth which largely determine whether or not primary twinning develops and the frequency of primary twin lamellae. Formation of primary twins is favored by euhedral growth and by rapid crystallization. Slow crystallization and anhedral growth tend to inhibit development of primary lamellae. Primary twinning on the albite and pericline laws is quite common in igneous plagioclase, but is uncommon in metamorphic plagioclase.

Glide lamellae in plagioclase are typically of uniform thickness and characteristically stand in genetic relation to bending or other deformation of the crystal. They differ markedly from primary lamellae, usually permitting easy distinction. Texture is an important factor in determining abundance of glide lamellae in the plagioclase of deformed rocks. In both igneous and metamorphic plagioclase, glide twinning on the albite law is exceedingly common and is usually associated with somewhat less abundant glide twinning on the pericline law.

INTRODUCTION

It has long been recognized that some polysynthetic twinning in plagioclase is of secondary origin. Glide twinning was first clearly demonstrated by van Werveke in 1883, and in 1931 was produced experimentally by Mügge and Heide. Since van Werveke's early observations many petrographers have confirmed his evidence, so that today the existence of secondary twinning is generally accepted. More recently, however, several workers have taken the extreme position that most and perhaps all polysynthetic twinning in plagioclase is secondary. These include Baier (1930, p. 494), Köhler and Raaz (1947, p. 169), Köhler (1949, p. 598), Emmons and Gates (1943, p. 288), and Emmons and Mann (1953, p. 41). Representative of this view is the statement of Köhler and Raaz,—"dass polysynthetische Zwillinge—das gilt nicht nur für die Plagioklase-niemals primär gewachsen sind, sondern das Ergebniss sekundärer Prozesse sind."

Other petrographers either endorse the opposing view that some and perhaps most polysynthetic twinning is primary or imply such without specifically noting the problem. Along with these investigators, the writer had assumed that most polysynthetic twinning in plagioclase was a growth phenomenon and thus primary. Surprisingly, a search of the literature failed to reveal any really cogent evidence for a primary origin. Is the theory of primary origin a mistaken one which has been uncritically accepted, or can it be demonstrated by direct petrographic evidence? The problem has considerable significance in petrogenesis. Gorai (1951), on the tacit assumption that twinning in plagioclase is primary, has statistically compared the twinning habit of plagioclases in a large number of igneous and metamorphic rocks. If all or some of this twinning is secondary and only accidentally superimposed on the plagioclase independent of its crystallization, his conclusions may justly be questioned. Starting with the assumption that polysynthetic twinning is secondary, Emmons and Mann (1953) arrive at other petrogenetic interpretations which are open to similar criticism. Over the years a number of useful articles have appeared dealing with the frequency of the different twin laws in various plagioclases. In these, the origin of the plagioclase (plutonic, volcanic, metamorphic, etc) has been considered, but the equally critical problem of the origin of the twinning has again been generally ignored. If both primary and secondary twinning do occur, criteria must be established by which they may be distinguished. By detailed study of individual rocks it may become possible to frame valid, if more limited, generalizations as to the petrogenetic significance of polysynthetic twinning. Failure to consider the origin of plagioclase twinning, whether primary or secondary, and the conditions responsible for its formation is clearly to ignore a major problem of plagioclase genesis.

This paper is submitted as a review and criticism of some aspects of the problem of twinning genesis, with emphasis on the criteria for distinguishing between primary and secondary twinning and the genetic factors which determine the twinning. In particular, it presents a new line of evidence in support of primary polysynthetic twinning. Other significant new contributions are the role of growth habit as a factor in primary twinning, and the importance of textural controls in glide twinning. The evidence adduced here is largely petrographic. No exhaustive review of the problem as found in a diffuse and voluminous literature is intended. Of the ideas expressed here, some are frankly speculative while others are at variance with the generally accepted views on twinning. The writer is aware of the breadth of the problem and the limitations of the data presented. Consequently some of the conclusions reached are tentative and all deserve scrutiny in the light of more detailed investigation. This study will have been successful if it does nothing more than bring awareness of the problems of plagioclase twinning and indicate some of the points to be considered in their final evaluation.

Primary Polysynthetic Twinning

General statement

Primary twinning (the growth twinning of Buerger, 1945, p. 473) develops as the result of addition of individual atoms or small groups of atoms to a growing crystal. Primary twinning is contrasted to secondary twinning in which an already formed or partially formed crystal develops twins through processes other than simple growth. The literature offers little discussion of primary polysynthetic twinning in plagioclase. Only a few petrographers—*e.g.* Barber (1936, p. 257) and Turner (1951, p. 587)—consider specific evidence for primary origin, and most of this is far from conclusive. Barber believes that the occurrence of vicinal composition faces demonstrates primary twinning, but this seems less than compelling in view of our present meagre understanding of vicinal phenomena and of the genesis of primary twinning itself. Certainly many secondary glide lamellae—*e.g.* pericline lamellae as well as long, slender, regularly tapering albite lamellae which are obviously related to the bending of a crystal—also have composition faces diverging slightly from rational crystallographic directions.

Evidence for primary twinning

Criteria for primary twinning can be developed from considerations of crystal morphology. Baier (1930, p. 483) appreciates this when he notes that "sie (primary twinning) steht meist in deutlicher Beziehung zu einem einspringenden Winkel der äusseren Umgrenzung." Thus, there should be, in euhedral crystals with primary twinning, a regular relation between the distribution of twin lamellae and external morphological form, and especially an occurrence of re-entrant angles at twin boundaries. This is true, of course, for primary twinning, but it is also true for secondary glide twins, as visualization of the well known experiment of artificial twinning of calcite will show. In itself, then, this relation proves neither primary nor secondary origin of the lamellae. It does, however, become significant when considered with other details of both external and internal crystal morphology.

The relations between twinning and zoning are of particular significance. In this paper, as traditionally, euhedral zoning is considered to be a primary feature and to mark the various stages in crystal growth. Powerful evidence supports this view. Euhedral zones are just as logically growth features as are the external crystal faces which they parallel. Further, the variable width and composition of different zones are much better understood as the result of a changing physical and chemical environment around a growing crystal than as superimposed secondary features. The very differences in the degree of development of the various "crystal faces" in one zone as compared to corresponding "faces" in adjacent zones rule out any hypothetical inward migration of secondary zones parallel to the crystal faces. Finally, it is difficult even to imagine a secondary process which could impress euhedral oscillatory zoning on earlier crystals. Irregular zones in igneous plagioclase which truncate earlier zones and are logically interpreted as due to resorption become inexplicable if referred to processes postdating crystal growth. The continuity of individual zones of distinct composition around doubly or multiple cored aggregates of plagioclase grains is readily understood as the result of coalescent growth (Vance, 1957, p. 1849), but is incomprehensible if zoning is secondary.

Zoning can thus be expected to show the same relation to twinning as does the external morphology, but with the advantage that it reveals the relations between twinning and crystal form during crystal growth (internal morphology). There is also the practical advantage that euhedrally zoned crystals are much more common than crystals with euhedral outer form.

A systematic relation between twinning and zoning was revealed during routine determination of the composition of euhedrally zoned plagioclase in a large group of igneous rocks, principally Tertiary quartz diorites, granodiorites, basalts, andesites, and dacites from western Washington. In each thin section plagioclase crystals cut normal to the *a*-crystallographic axis were located for extinction angle measurement. These (*a*-normal) sections are easily recognized in that they are perpendicular to both the (001) and (010) cleavages (Fig. 1 A–D). In *a*-normal crystals which show albite twin lamellae the (001) cleavage zigzags abruptly at each twin boundary and deviates about 8° from a straight line (Fig. 1 A, C, D). In *a*-normal sections with pericline twinning, (no attempt has been made to separate pericline and acline twins in this paper), the (010) cleavage switches its position from twin to twin in a similar way (Fig. 1 B, C). In every case where these oriented sections show sharply marked euhedral zoning, it was found that zones parallel to (001) and (010) rigidly follow their respective cleavages in making the zigzag shift in trend across twin boundaries (Fig. 1 A–D). Similar relations were found in plagioclase crystals with euhedral outer form; here, however, not only the zones but also the (001) and (010) crystal faces (in albite and pericline twinning respectively) change position from one

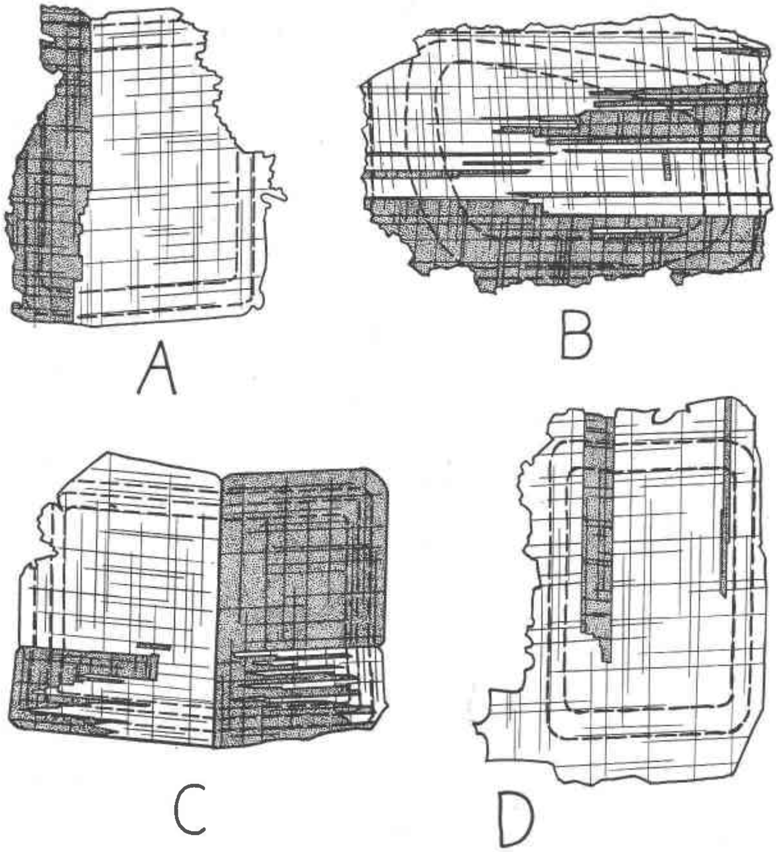

FIG. 1. Relations of euhedral zoning and primary twinning in *a*-normal sections of plagioclase. (010) is oriented near vertical, (001) is oriented near horizontal. Note the parallelism of the cleavage and zoning (generalized by dashed lines). All the plagioclases are igneous and show oscillatory zoning with a normal trend.

A. Simple albite twinning in andesine (An_{49}-An_{27}) from Tertiary quartz diorite, Monte Cristo, Washington. Width of grain 1.7 mm.

B. Pericline twinning in andesine-oligoclase (An_{41}-An_{17}) from the Tertiary Squire Creek quartz diorite Darrington, Washington. Width of grain 2.5 mm.

C. Albite and pericline twinning in andesine (An_{45}-An_{34}) from a vitrophyric hypersthene andesite dike north of Glacier Peak, Washington. Width of grain 1.4 mm.

D. Albite twinning in andesine-oligoclase (An_{40}-An_{16}) from the Squire Creek quartz diorite, Darrington, Washington. Width of grain 0.4 mm.

twin lamella to the next (Fig. 1 C). When these relations had become apparent, approximately 200 additional thin sections showing plagioclase with euhedral oscillatory zoning were checked. Normal calc-alkaline igneous rocks were used exclusively and the relations were found to be consistent for both volcanic plagioclase (An_{30}-An_{60}) and plutonic plagioclase (An_{20}-An_{55}). A large number of thin sections was necessary because only about one out of five showed crystals suitably combining the polysynthetic twinning, proper orientation, lack of alteration, and sufficiently sharp zoning necessary to conclusively establish the relations between twinning and zoning. However, every crystal which did fulfill these conditions revealed the same rigid parallelism between zones parallel to (001) and (010) and the respective cleavages. Altogether some 50 clear-cut examples were found.

This close and consistent relation between polysynthetic twinning and zoning is compatible with either primary (growth) twinning or secondary glide twinning. In almost half the crystals showing this twin-zone relation, however, some of the lamellae concerned do not traverse the entire crystal but pinch out step-like in a blunt irregular manner, within the crystal. In the *a*-normal sections studied this tendency to terminate within the grain is especially marked in the pericline lamellae, but is also seen in the albite lamellae, though to a lesser degree. These terminated lamellae are not thin and regular or gently tapering, as characterizes most secondary glide lamellae, nor are they associated with bending, twisting, or fracturing of the crystal as is so general with secondary lamellae. (See Table 1 for a comparison of the characteristics of primary lamellae and glide lamellae.) Where several lamellae terminate within a crystal, they do so independently of one another, unlike glide lamellae which almost universally show a systematic distribution within the crystal and a regular sense to the direction of pinch-out. The crystals studied, even near the terminated lamellae, reveal no indication of the bending and strain so characteristically associated with glide lamellae. Since these lamellae terminate without strain, the crystal being undisturbed along their projected continuation, the twinning is considered to be primary. Additional evidence of primary origin is revealed by an examination of either the gross outer form of the crystal or of the zonal outline in crystals with terminated lamellae. A re-entrant angle is associated with each of the terminated lamellae in Fig. 1 B–D. This is readily understood if the lamellae are primary, while a mysterious diminution in volume of part of the crystal—an exceedingly unlikely occurrence—must be invoked if the lamellae are considered to be secondary. Finally, it is to be stressed that, if the twinning in these crystals were glide twinning, both the crystals themselves and adjacent crystals in the fabric would show cataclastic effects where the new lamellae had made room for themselves. Such strain features are lacking in the rocks studied, except insofar as entirely later glide twinning and deformation may have developed in some specimens. (Generally at least a few extremely narrow,

TABLE 1. COMPARISON OF PRIMARY LAMELLAE AND GLIDE LAMELLAE IN PLAGIOCLASE

Primary Lamellae	Glide Lamellae
Twinning is simple, or, if multiple, lamellae are few.	Twinning is multiple and lamellae are usually numerous.
Lamellae in individual grains vary widely in thickness.	Lamellar thickness is essentially uniform within each set of lamellae or for all lamellae in individual grains.
Lamellae are usually rather broad and coarse. They often change width or terminate within the crystal abruptly and irregularly.	Lamellae are slender and may be extremely fine. They are usually very regular and may traverse the entire grain with uniform thickness.
Lamellae thicken and thin independently of each other. The changes in width are step-like and abrupt and unrelated to later bending.	Lamellae thicken and thin gradually and regularly, in unison, and in the same direction, often in conjunction with bending of the crystal.
Individual lamellae terminate independently of each other and without relation to later bending or fracture.	Lamellae terminate regularly as long tapering points which are often localized in areas of bending and may be bent themselves. Termination and changes in thickness are common across fractures.

regular glide lamellae, presumably due to stresses set up during contraction with cooling or inversion, were also present in the igneous plagioclases studied, and broader, more abundant glide lamellae were found in all rocks showing stronger deformation. Such glide twinning may completely obscure an earlier generation of primary lamellae. This later twinning, however, does not bear on the origin of the primary features discussed here.)

For these reasons it is believed that the albite and pericline lamellae studied are primary and thus, that these crystals grew twinned. Strictly this conclusion applies only to the specific *a*-normal crystals described, but it is reasonable to conclude that twinning is also primary in other plagioclase crystals in the same rocks, at least in so far as the twinning characteristics are comparable and evidence of secondary twinning is lacking. These relations between twinning and zoning provide a quick and simple petrographic method by which primary polysynthetic twinning in plagioclase may be established in euhedrally zoned material. These relations are by no means anomalous or unexpected, but are demanded by the triclinic symmetry requirements of the albite and pericline laws. Implications of these twin-zone relations with regard to transformation twinning are considered below. It is to be hoped that eventually some line of evidence, other than the negative evidence of the absence of definite indications of secondary lamellae, can be developed to establish primary twinning in plagioclases which lack euhedral zoning and euhedral outer form.

In the material studied, primary albite and pericline (including acline) lamellae appear to be about equally common. The frequency with which primary polysynthetic twinning was encountered in the rocks studied indicates that it is quite common in igneous plagioclase.

The origin of primary twinning

The causes of primary polysynthetic twinning must be sought in terms of environmental conditions and in the process of crystal growth itself, rather than in secondary factors such as inversion or exposure of the finished crystal to mechanical stress. Buerger (1945, p. 473), has given a convincing theoretical explanation of primary twinning in which the rate of growth is considered the principal controlling factor. According to this theory, formation of primary twinning is favored by rapid growth and minimized by slow growth. Minimum energy requirements are fulfilled when atoms are added to a growing crystal in parallel position so as to continue the initial pattern. There are, however, other positions—twin positions—in which atoms can be added in coordination with those atoms already present without continuing the earlier pattern. Atoms added in this way do not quite meet the lowest energy condition and thus tend to be dislodged and replaced by more favorably oriented ones. If, however, an already coordinated group of atoms joins the growing crystal in the position of near minimum energy, it may remain in place, being more stable than a single atom. This twin will grow if joined by other atoms in the same orientation. Other conditions being equal, the probability that newly arrived atoms or groups of atoms will persist in twin position is the greater the more rapid is the addition of atoms and thus, the more rapid the growth. Buerger further states that since crystal growth is rapid in the earliest stages when nuclei first develop under conditions of supersaturation, twins may then be initiated which persist and continue to grow in the following period of slower growth. The simple albite twins in Fig. 1 C in which the composition plane passes through the center of the crystal may be of this sort. This situation, however, is not typical and recurrent supersaturation, leading to rhythmic growth, may be more general than appreciated by Buerger, (see Padurow, 1949, p. 212), so that lamellae may be initiated as a result of rapid growth at various stages of crystallization. Oscillatory zoning, as recognized by Harloff (1927), Phemister (1934), and Hills (1936), strongly suggests such rhythmic supersaturation for igneous plagioclase.

Buerger's theory clarifies many features of primary polysynthetic twinning (See Table 1), which would otherwise be puzzling. Variable rates of crystallization could account for differences in twinning habit of compositionally similar plagioclases in rocks of the same composition. Both the characteristic variation in width and the blunt termination and abrupt change in thickness of primary lamellae are explained by this theory. Primary lamellae of unequal width are obviously to be expected where variations in the rate of growth are more or less random causing initiation of twins irregularly through time. Uneven lamellae will also generally develop even where variations in the rate of growth are regular and periodic, for the tendency is always to satisfy the minimum energy condition and for growth to continue the untwinned configuration. It is therefore improbable that primary lamellae will always be initiated on both sides of the crystal simultaneously. The possibility of even lamellar thickness is, in fact, so foreign to primary twinning that regular, uniform lamellae are an almost conclusive indication of secondary origin. Abrupt change in thickness and blunt termination of lamellae result where, during lamellar growth, the twin orientation is maintained in only one direction and is lost in the other to the original untwinned configuration by irregular transgressive growth of the twin composition surface. Primary lamellae change thickness quite independently of each other, unlike glide lamellae which thicken and thin in unison. Sharply parallel continuous lamellae might be favored by rapid growth which initiates the twins, followed by slower growth which causes them to develop regularly throughout the remainder of crystallization. Episodic growth resulting from recurrent supersaturation—and this appears to be the most usual case in igneous plagioclase—would tend to produce a relatively few twin lamellae of unequal width, many of which terminate within the crystal or abruptly change thickness.

Buerger's theory of variation in the rate of growth accounts very adequately for many characteristics of primary twinning in crystals with euhedral growth habit. In anhedrally grown plagioclase, however, growth habit, the form of the crystal during its growth, appears chiefly responsible for the general absence or scarcity of primary lamellae. Anhedral growth is reflected in irregular grain boundaries during crystallization. On an atomic scale this implies relative irregularity in the surficial layer of atoms—such that many indentations and unoccupied positions are present. These anhedral surfaces cut across the directions of the potentially most stable surfaces in the crystal, those of possible crystal faces. Clearly such anhedral surfaces have a higher surface energy than euhedral faces. Since a still higher energy condition will necessarily result from the addition of atoms in twin position, it is apparent that initiation of twins should be less frequent on growing anhedral faces than on euhedral ones. This is only a tendency, of course, and, in addition to the irregularity of surface, factors such as rate of growth will influence the number of lamellae initiated and, indeed, whether or not twinning is developed at all. Surface irregularities would have other effects as well. Small gaps in the surface where one or several atoms are missing are unlikely to be filled with atoms in twin position due to the difficulty of lateral coordination with the adjacent atoms. Even if added in this manner, the twin could not be extended in all directions laterally by growth, since some of the adjacent positions are already occupied by atoms in the original untwinned configuration. Irregular surfaces are also less likely to have a form conducive to the addition of groups of already coordinated atoms whether this be in parallel or in twin position. Anhedral growth, while it cannot, perhaps, entirely exclude the formation of primary twinning, clearly discourages development of numerous lamellae.

These theoretical considerations find abundant empirical confirmation, for primary twinning appears to be almost entirely restricted to plagioclase which, as demonstrated by the zoning, grew euhedrally. Primary twin lamellae are typical not only of the usual euhedrally zoned igneous plagioclases, but of the few euhedrally zoned metamorphic plagioclases examined. The much more common anhedrally zoned metamorphic plagioclase showed few or no primary twin lamellae. The dependence of the frequency of primary twin lamellae on growth habit may well amount to a rigid control. Examination of over 150 thin sections of metamorphic plagioclase with anhedral zoning (chiefly schists, amphibolites, and gneisses from the Northern Cascades of Washington revealed that, after excluding specimens in which polysynthetic twinning was clearly secondary, few of the remaining sections showed much, if any, twinning. Even if all the remaining twinning in these plagioclases is considered to be primary, it is apparent that primary lamellae are conspicuously subordinate in the plagioclase which grew anhedrally. Other workers—Köhler (1948, p. 62) and Turner (1951, p. 581)—have also noted the tendency for many metamorphic plagioclases to be little twinned or untwinned.

Although zoning has been useful in relating polysynthetic twinning to growth habit, it must be emphasized that growth habit, not the zoning itself, controls the twinning. This is apparent in both the igneous and metamorphic plagioclases studied, for the type of zoning (normal, reverse, or oscillatory), the degree of compositional difference in the zoned crystals, and the number and thickness of the zones proved to be essentially independent of the frequency of the lamellae. Euhedrally zoned crystals of igneous plagioclase with a wide compositional range in zoning did not appear to differ systematically in frequency of lamellae from other euhedrally zoned crystals with an almost imperceptible compositional range. This suggests that the degree of zonal compositional difference is unrelated to the number of lamellae developed and that even unzoned plagioclase which grew euhedrally would have similar twinning. In the same way, anhedrally grown metamorphic plagioclase which ranges in different rocks from sodic oligoclase to medium labradorite and which is partly zoned and partly unzoned proved in general to be scantily twinned or to lack primary lamellae entirely. Since zonal form appears to be the only feature of zoning to which the frequency of primary lamellae can be systematically related, growth habit must be considered the decisive factor.

The dependence of primary twinning on growth habit may well amount to a general control applying to other minerals besides plagioclase. Hornblende with euhedral growth habit, as is typical of most igneous hornblende, appears to be twinned more often than metamorphic hornblende which more commonly has an anhedral growth habit. It likewise appears significant that epidote, kyanite, and staurolite, metamorphic minerals which commonly are idioblastic and have grown euhedrally, are often twinned.

Secondary Polysynthetic Twinning

General statement

Several types of secondary twinning are theoretically possible in plagioclase. To discover which types actually occur, each specific type must be considered in the light of the available evidence. Buerger (1945, p. 477) recognizes two types of secondary twins, gliding twins and transformation twins; these latter develop when rearrangement of atoms during inversion of a high to a low form leads to configurations which are in twin relationship. It may be noted here that some investigators (Baier, 1930, p. 483; Eitel, 1958, p. 119) fail to clearly differentiate between transformation twinning and glide twinning, two entirely different genetic classes of secondary twinning. A third and much less widely appreciated genetic type of secondary twins includes those formed by the drifting together and joining of crystals in a magma according to a twin law. These *synneusis twins*, the "combination twins" of Ross (1957, p. 650), are not considered here, however, as they do not typically lead to polysynthetic groupings in the usual meaning of the term. The abundance of Carlsbad twins in igneous plagioclase and their contrasted infrequency in metamorphic plagioclase can only be due to their frequent origin by synneusis, a process operative only in a fluid medium where free movement of crystals is possible. Some examples of chessboard albite with which I am acquainted appear to be the result of incipient recrystallization of plagioclase in which small patches within earlier lamellae have recrystalized in twin orientation. Although, in a sense, the twinning of such chessboard albite may be regarded as in part secondary, this constitutes a separate problem which will not be considered here.

Glide twinning

Van Werveke's (1883) early demonstration of polysynthetic glide twinning in plagioclase has since been supported by a large body of data including work by Judd (1887), Fedorow (1899, p. 365), Colomba (1908) Baier (1930, p. 480), Chudoba (1931, p. 488), Harker (1932, p. 164), Emmons and Gates (1943, p. 290), Turner (1951, p. 583), and many others. As a final confirmation, Mügge and Heide (1931) have artificially produced both albite and pericline glide lamellae in natural plagioclase.

Secondary glide lamellae usually show distinctive characteristics permitting easy recognition in thin section. These lamellae often terminate at cracks within the crystal and fail to match in either number, width, or relative distribution across these cracks (Fig. 2, A, B). These cracks permitted a different mechanical response to deformation in the separated parts of the crystal and are clearly older than the twinning. Even more commonly secondary lamellae are genetically related to an evident bending or twisting of the crystal such that the lamellae are localized and most broadly developed in the areas of greatest strain (Fig. 2 B–F) while they pinch out or are only scantily developed in the unstrained or more weakly deformed parts of the crystal. The distribution of these lamellae is inseparably linked to the deformation of the crystal, and finds no conceivable explanation in terms of any mechanism of development of the twins during crystal growth. These glide lamellae usually taper to very long, fine points which commonly are bent and transect the direction of the usual composition plane—(010) in albite twinning, the rhombic section in pericline twinning—at a slight angle. In groups of such narrow secondary lamellae, the individuals either thicken, thin, or wedge out in a concerted fashion, most often in areas of obvious bending. This behavior is entirely different from that of primary lamellae which terminate independently of one another—more often somewhat bluntly and irregularly than as regular slender wedges—and which, if bent, show no relation between changes in thickness and any bending which is present. A final characteristic of secondary polysynthetic twinning, as noted by Baier (1930, p. 480) and others, is the tendency of the lamellae to be slender and of rather uniform and regular thickness. This regularity reflects relatively homogeneous release of stress in the deforming plagioclase and is incompatible with a primary origin of the lamellae. Primary

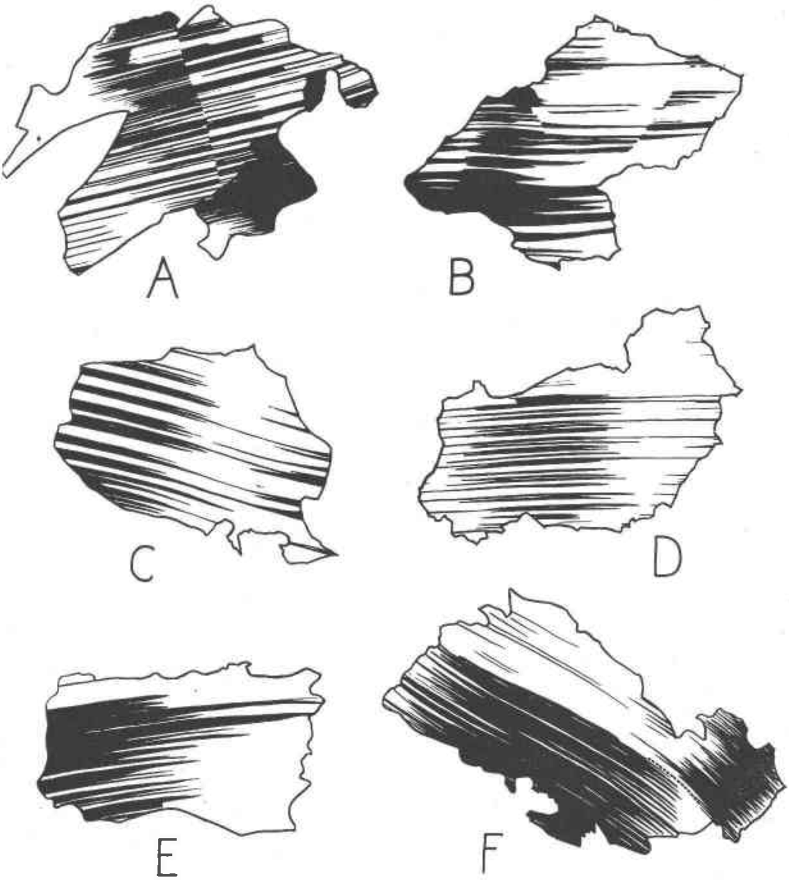

FIG. 2. Representative examples of glide twinning in plagioclase. Twinning postdates crack in A and B (right-hand side). Twinning in B-F shows clear genetic relationship to bending. A–D albite twinning. E pericline twinning. F combined Carlsbad-albite twinning.

A. Andesine (An_{41}) from garnet-bearing quartz dioritic gneiss, Whitechuck River, Washington. On lower right is separate small grain. Width of grain 2.5 mm.
B. Andesine from same specimen as A. Width of grain 2.6 mm.
C. Andesine (An_{33}) from quartz diorite near Entiat, Washington. Width of grain 0.7 mm.
D. Andesine (An_{37}) from quartz dioritic gneiss, Whitechuck River, Washington. Width of grain 1.9 mm.
E. Andesine (An_{39}) from same specimen as A. Width of grain 1.1 mm.
F. Andesine, oscillatory zoning with one recurrence (An_{38}-An_{46}). Same specimen as A. Width of grain 2.7 mm.

lamellae, as the result of the temporally more or less sporadic and random twin initiation (and termination) characteristic of growth twinning, typically vary widely among themselves both in width and continuity within a single crystal. Curiously, when both sets of glide lamellae are about equally developed it usually cannot be determined which set represents the original and which the twin orientation.

There is an interesting feature of some glide twinning which is not discussed in the literature, although occasionally figured there (*e.g.* the *a*-normal section shown in Emmons and Gates, 1943, p. 300, Pl. 1, Fig. 3). This is the development of so many secondary glide lamellae on one end of a plagioclase crystal that they essentially merge into one broad lamella, and the entire end of the crystal goes over into the new "twin" position. Figure 2 E of the present paper shows incipient development of this condition. With continued deformation such crystals may actually become "untwinned" in the sense that an earlier twinning is lost. These crystals, initially undeformed, become strained with simultaneous bending and development of glide lamellae. With further deformation the lamellae coalesce involving more and more of the crystal which finally becomes unstrained as the bending and secondary lamellae are eliminated and the twin orientation is assumed by the entire crystal. Characteristically associated with this process, as with glide twinning in general, are marked cataclastic and strain effects on adjacent crystals produced as room is made to accommodate the crystal in its new position. The general characteristics of primary and secondary lamellae, as determined from observation of a large number of twinned crystals, are compared in Table 1.

When the features described are abundant in a thin section and the twinning shows a general uniformity from crystal to crystal, it may be presumed that much, and perhaps most, of the plagioclase has undergone glide twinning. It is evident, of course, that not every random slice of a plagioclase crystal with glide twinning will show positive evidence for its origin. On the other hand, if secondary twinning in a rock is at all prominent, many other crystals will be diagnostic. Without strong evidence, it cannot be assumed that every crystal in such a section has undergone secondary twinning or that all the lamellae are secondary. The possible presence of an earlier generation of primary lamellae, or even of earlier secondary lamellae, should not be overlooked. Diligent examination will sometimes permit distinction of these two. It is anticipated that detailed analysis of the mechanism of twin gliding in plagioclase, a problem now largely untouched, will greatly extend the usefulness of the petrofabric field for the petrographer.

As judged by the criteria developed, glide twinning is much more common than primary polysynthetic twinning, and albite glide lamellae are considerably more abundant than pericline glide lamellae. Primary lamellae are rarely developed except in euhedrally grown crystals which largely restricts them to igneous plagioclases, and even here later superimposed glide twinning is generally present and may obscure or eliminate all traces of the primary twinning. Glide twinning, by contrast, is very widespread in both igneous and metamorphic plagioclase.

Origin of glide twinning

In rocks which have otherwise experienced the same degree of deformation, the texture of the rock is believed to be a significant control of glide twinning. This became apparent from study of anhedrally zoned and unzoned metamorphic plagioclase from the Northern Cascades of Washington. Over 200 specimens of isochemical and metasomatic rocks were investigated. These rocks occur closely interlayered in a migmatitic terrane and clearly have both participated equally in post-crystalline deformation. The relatively coarse, irregularly bounded, interlocking plagioclase grains of the inequigranular feldspathized schists and metasomatic gneisses examined were found to exhibit abundant secondary glide lamellae. However, the finer-grained, more equant plagioclase in the isochemical schists and amphibolites studied showed distinctly fewer secondary lamellae and in many of these rocks was largely untwinned.

The differing textures of these contrasting rock types are thought to be responsible for the variable susceptibility to secondary twinning. Stress in the finer-grained isochemical rocks is taken up in rotation of the more or less round, equant plagioclase grains, while the large interlocking plagioclase grains which dominate the fabric of the metasomatic gneisses cannot escape strain in the form of crystal bending and concomitant twin gliding. The mechanical properties of the other minerals present appear to have played an important modifying role in determining the extent of twin gliding in the plagioclase. Minerals such as quartz and biotite when present in considerable amount tend to take up most of the strain leaving the tougher plagioclase relatively undeformed. Gorai, (1951, p. 891), notes that the frequency of twinned plagioclase varies directly with the grain size in the metamorphic rocks that he has studied. It is quite possible that his twinning is largely secondary and that the abundance of lamellae depends not so much on grain size but on the related factor of the degree to which the feldspar crystals are interlocking. Similar relationships may apply in the Adirondack paragneiss studied by Engel and Engel (1960, p. 14). In the finer-grained, relatively equigranular phases of this paragneiss the plagioclase shows only minor polysynthetic twinning, while it is abundantly twinned in the coarser-grained, more inequigranular varieties richer in plagioclase.

Many processes have been invoked to account for the stresses producing glide twinning. Deformation of the plagioclase by forces external to the rock as a whole is most often cited and clearly the most significant single process. Other suggested processes, some of rather dubious merit, may be mentioned briefly with no attempt at evaluation. These include differential contraction upon cooling of phenocrysts or interlocking grains (Alling, 1936, p. 157), stresses set up within crystals upon either heating or cooling (Baier, 1930, p. 480), stresses caused by mutual interference of grains during crystal growth (Taylor, Darbyshire, and Strunz, 1934, p. 494; Chapman, 1936, p. 42), and stresses set up by vesiculation of lava or by the flow of viscous magma or small crystals against phenocrysts (Emmons and Gates, 1943, p. 293 and p. 295). Volume increase of phenocrysts upon sudden decrease of confining pressure on a magma could also possibly lead to glide twinning. Finally, glide lamellae may probably form due to differential stresses set up by contraction during high-low inversion. These lamellae are the result of deformation of the crystal (by volume decrease) and involve mechanical displacement of the crystal within one set of lamellae. Such lamellae must not be confused with transformation twins which develop through small-scale atomic rearrangement. In consequence of its larger decrease in volume such inverted plagioclase should show a stronger development of glide lamellae due to contraction than either quenched plagioclase or plagioclase which has grown below its inversion.

Transformation twinning

The view that polysynthetic twinning in plagioclase may form through transformation, that is, inversion of the high-temperature to a low-temperature form, has wide currency. The mechanism of this twinning, however, is seldom clearly stated. Adhering to Buerger's definition (1945) of transformation twinning the twin configuration must arise through small-scale rearrangement of atoms during inversion. Glide twins, even though caused by stresses set up by inversion, do not meet this definition. Köhler and Raaz (1947, p. 169) envision twin formation through the inversion of a monoclinic or nearly monoclinic plagioclase to its present triclinic form. Buerger (1948, p. 120) notes that albite and anorthite have a common high-temperature form which may well be monoclinic and that both albite and pericline twinning may be related to inversion. Tuttle and Bowen (1950, p. 583) remark that the nature of the twinning should certainly be different when the crystals have grown below their inversion, as compared with that developed when they are inverted from the high-temperature modification. According to Buerger (1945, p. 481) the transformation from the monoclinic orthoclase structure to the triclinic albite structure requires only slight structural displacements in the order of magnitude of heat motion. If the postulated inversion involves, instead, the transformation of a more nearly monoclinic plagioclase to a plagioclase of lower symmetry, then the required structural displacements presumably would be still smaller.

It appears significant that none of the writers cited presents any evidence for transformation twinning in natural plagioclase. Muir (1955, p. 563) and other workers have produced extremely fine, secondary albite and pericline lamellae by heat-treatment of low- and intermediate-temperature plagioclase. This secondary twinning, however, is almost certainly glide twinning caused by stresses set up in the low-high inversion, and cannot be true transformation twinning which must develop on inversion of the high to the low form. Polysynthetic twinning does occur in synthetic plagioclase (Tuttle and Bowen, 1950, p. 574; Laves and Chaisson, 1950, p. 585), but it is by no means certain that this is not glide twinning.

It is especially significant that, although inversion of low-temperature plagioclase to the high-temperature form has been produced artifically in albite by heating above 700° C. (Tuttle and Bowen, 1950), attempts to produce the high-low transformation, much less to synthesize low-temperature albite, have been singularly unsuccessful. It remains problematical how far generalizations based on *x*-ray-determined structural changes produced on the heating of plagioclase can be carried over to presumed structural changes in the cooling of natural plagioclase, changes which are not reproducible in the laboratory. Thus, the question of whether plagioclase shows transformation twinning is closely tied to the larger question of whether inversion itself can be demonstrated to have occurred in the cooling of natural plagioclase, and, if so, what is the extent of the structural changes involved. The cleavage-zone relations described in the section on primary twinning have a direct bearing on this problem.

The best evidence for transformation twinning lies in the fact that inverted plagioclase should, in its morphology, preserve some "memory" of high-temperature origin (*c.f.*Tuttle and Bowen, 1950, p. 583). Since inversion presumably involves only slight structural displacement of atoms, the original "monoclinic" or "more nearly monoclinic" form should be preserved both by the zones and in the external morphology, just as the high-temperature symmetry is preserved in euhedral crystals of inverted high quartz. In inverted crystals these elements of original high-temperature symmetry will be contrasted with the present low-temperature structure and lower symmetry. These younger elements may be discovered by *x*-ray studies and more simply by cleavage which is determined by the present structure. Thus, *a*-normal sections of zoned plagioclase which have undergone inversion should show a lack of parallelism of the (001) and (010) cleavages which represent the present structure, with regard to their respective zones and crystal faces which reflect the primary structure. Similarly, in *a*-normal sections with transformation twinning, euhedral zoning, the primary element, should pass undeflected across the twin lamellae. If natural high-low inversion of plagioclase and transformation twinning are to be demonstrated, the evidence must lie in relations of this kind.

Study of a large number of thin sections of normal volcanic and plutonic igneous rocks revealed more than 50 zoned plagioclase crystals which clearly cannot have undergone inversion in anything like the sense generally visualized. It will be recalled that *a*-normal sections of zoned crystals showed a sharp parallelism between both (001) and (010) cleavages and their respective zones (as well as crystal faces when such were present), even across albite and pericline lamellae (Fig. 1 A–D). These zones and faces are primary features and demonstrate that the crystal was triclinic when it grew. The cleavage, which expresses the internal structure of the crystal (after any presumed inversion), is equally triclinic. Since the zones and cleavages are sensibly parallel optically, the inference is clear that neither crystal symmetry nor structure have changed appreciably, but that instead the plagioclase crystallized initially in the same or very nearly the same triclinic form it now exhibits. The plagioclase either has not inverted at all, or the structural changes measured in terms of crystal morphology have been so slight as to be negligible. It is certainly clear that these plagioclases were never monoclinic. Since these crystals show no evidence of significant inversion, there is no reason to suppose that other plagioclase crystals in the same rocks have experienced any profound inversion either, and there is every reason to suspect they have not. However, quite apart from the problematical question of inversion and the magnitude of the structural changes involved, it is obvious that the described twin lamellae across which the zones are deflected cannot have formed by small-scale atomic rearrangement upon inversion and thus cannot be transformation twins.

The evidence against any marked structural change in inversion of the plagioclases studied appears significant, for the many igneous rocks examined comprise ordinary dacites, andesites, basalts, granodiorites, and quartz diorites and can in no way be considered abnormal. On the basis of occurrence, both high-temperature plagioclase (An_{30}–An_{60}) and low-temperature plagioclase (An_{15}–An_{55}), (Köhler, 1941), may be represented. If these plagioclases have not markedly inverted, one may wonder what the general order of magnitude of structural change is in the inversion of natural plagioclase. In any case, we may reserve some skepticism for unsupported statements about transformation twinning and inversion in natural plagioclase.

It is necessary also to consder the unlikely proposition that inversion in plagioclase entails not merely slight structural displacement, but the large-scale rearrangement of a reconstructive transformation. Such a process could conceivably account for the relations observed between cleavage and crystal and zonal form. However, the volume of material displaced in producing twinning and altering the crystal symmetry in such a transformation would greatly exceed that associated with glide twinning and would, in fact, be so great as to amount to complete recrystallization. Primary zoning in the crystal could scarcely survive this redistribution, if anything, the plagioclase should tend to become homogeneous. In the crystals studied, however, the delicate zonal features are sharp and intact. As already discussed, many characteristics of the zoning are such as to preclude a secondary origin, and, in any case, secondary molecular redistribution would tend to eliminate, not create, zoning. For structural reasons, discussed by Goldsmith (1952, p. 289), diffusion within plagioclase on the scale required here is highly unlikely even where magmatic temperatures are long maintained. The slight importance of diffusion in plagioclase is empirically supported by the general presence of delicate oscillatory zoning in igneous plagioclase—commonly even in plutonic rocks where crystallization and cooling from high temperature are presumed to be slow. This indicates that reaction between melt and crystal by diffusion as visualized in Bowen's scheme (1913, p. 597) is seldom, if ever, more than imperfectly realized. (These same considerations militate against any mechanism of elimination zoning in alternate twin lamellae as has been reported by Emmons and Mann (1953). In the examination of many thousands of zoned, polysynthetically twinned plagioclases cut normal to the composition plane I have always found perfectly uniform zonal development in both sets of lamellae.) Finally, such inversion would often occur with the plagioclase embedded in a solid crystal medium, as in glomeroprophyritic aggregates or groups of coalescent plagioclase grains. The change in outer crystal form attendant to this kind of inversion should produce cataclastic and strain effects on adjacent crystals at least as extensive as those developed in glide twinning. Such features are not developed in the rocks studied.

Plagioclase Structure and Twinning

A discussion of the origin of polysynthetic twinning would be incomplete without considering the theory that the abundance of twin lamellae varies as a function of plagioclase composition and thus is structurally controlled. The leading proponent of this idea is Donnay (1940 and 1943) who correlates the frequency of lamellae with crystallographic "obliquity" which varies with the degree of triclinicity, itself a function of plagioclase structure and composition. More recently Gay (1956) and Smith (1958) have extended Donnay's theory to include structural differences between the high- and low-temperature plagioclase series and to include metamorphic plagioclase. While these workers do consider some environmental factors in twinning, a dominant role is ascribed to internal, structural controls. In support of the structural control theory the generalizations of a number of petrographers are cited as to the variation of lamellar width with plagioclase composition. These generalizations are believed to conform to the predictions of the theory.

The evidence for the structural control theory fails in many ways to be compelling. No physicochemical basis has been given to explain why "obliquity" should be the major control of lamellar width. My own experience has not revealed the systematic regularity in lamellar width with composition which the other investigators have apparently seen. Exceptions to their generalizations are, in fact, so common as to bring the theory strongly in question. In addition, the generalizations are in many ways vague and say nothing on such critical matters as the relation of lamellar width to grain size without which lamellar frequency has little meaning. Most important of all, however, the structural control theory has entirely ignored the genesis of the twinning. To the present writer it appears that the major features of both primary twinning and glide twinning can be explained largely or entirely in terms of the genetic factors already discussed without appealing to structure.

In plagioclase with primary twinning, for instance, not only lamellar width, but lamellar form, and the very presence or absence of twinning appear adequately explained in terms of environmental factors alone. Primary twinning in the material studied failed to disclose any systematic variations in lamellar frequency which could conceivably be related to a compositional-structural control. In the igneous plagioclase studied, the width of the primary lamellae tends always to be large relative to grain size, without regard for composition. Far from reflecting uniform structure for all these plagioclases, this simply indicates that conditions of igneous crystallization do not generally favor development of numerous lamellae. This relation throws considerable doubt on the structural control theory with regard to the formation of primary lamellae. Because these conclusions are based on limited data, they must remain tentative and will require further investigation. It is significant, however, that a structural control finds no support in the primary twinning studied.

The structural control theory appears to rest on equally weak foundations as related to glide twinning. This is significant since glide twinning is by far the commonest type of twinning in plagioclase, and most of the twinning cited in support of the structural control theory is presumably of this origin. It is clear that any plagioclase regardless of composition, structure, or the presence or absence of earlier twinning, will develop glide lamellae if sufficiently stressed. In such material the width of the lamellae developed must depend largely upon the intensity of the stress applied and the distribution of this stress in the crystal, not upon plagioclase structure. The fact that metamorphic plagioclases which differ little among themselves structurally vary greatly in frequency of twinning and lamellar width (see above) serves to emphasize the importance of rock texture and deformation and to minimize the role of plagioclase structure as controls of glide twinning. Structural factors are, of course, indirectly involved in the formation of glide lamellae through contraction during cooling or inversion, inasmuch as they determine the magnitude of the stresses set up. The structural control here, however, is an entirely different thing than Donnay's "obliquity" factor.

The status of the structural control theory must remain uncertain until all factors, both structural and environmental, which bear on the origin of the twinning and on lamellar width can be evaluated for the data cited in support of the theory. It will also be necessary to conclusively establish the structure of the plagioclase at the time of twinning, a task which is certain to involve formidable problems. Eventually it may be possible to divorce the structural effects postulated by Donnay and his followers from the many other factors which determine lamellar width and to determine the relative importance of these controls. To date, however, this has not been done, nor can it be done with the incomplete and fragmentary data available.

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