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OPTICAL-CRYSTALLOGRAPHIC SCATTER IN PLAGIOCLASE

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ABSTRACT

Optical-crystallographic scatter in twinned plagioclase, expressed in stereographic form, is a meaningful tool in petrogenic interpretations. Internal scatter is the optical-crystallographic scatter between twin lamellae within a grain and is the result of an imperfect twin. This scatter occurs in all twin types from all environments.

External scatter is the most petrogenically revealing type of scatter. It is the optical-crystallographic scatter between different grains in the same sample. Most volcanic and regional metamorphic samples show only compositional scatter and contain no external scatter normal to the migration curves. The plots of these samples define the disordered and ordered migration curves for plagioclase. External scatter almost always occurs in coarse-grained, igneous-appearing rocks and is confined to the area between the migration curves. It is significant that in a single sample, the scatter can bridge the gap between the disordered and ordered migration curves.

External optical-crystallographic scatter within an individual sample is due to twinning during the ordering or disordering process. Most volcanic plagioclase do not have external scatter because the samples formed, twinned, and remained in the disordered state. Similarly the plagioclase of most regionally metamorphosed rocks have no external scatter because they twinned and remained at a specific structural state—the ordered state. Coarse-grained, igneous-appearing samples exhibit scatter because they have twinned throughout the ordering process.

INTRODUCTION

The optical-crystallographic scatter of plagioclase is a real and interpretable characteristic, dependent upon the environmental history of the rock, and useful as a petrogenic indicator.

Reinhard (1931) and Nikitin (1933) recognized that the plagioclase form a continuous series in which the relationship between the optical orientation and twinned elements varies with composition. Köhler (1941) noted that the optical orientation in volcanic plagioclase was markedly different from that of the standard plagioclase given by Reinhard (1931), and Van der Kaaden (1951) expanded this work to produce "high- and low-temperature" migration curves which have had wide publication and use. This type of work reached its zenith when Marfunin (1960) published "high- and low-temperature" curves connected by a network of isopleths showing the optical orientation relative to the degree of order-disorder of the plagioclase.

Crump and Kettner (1953), Glauser (1961) and the present study demonstrate that individual samples may contain sufficient scatter of

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the optical-crystallographic elements to cover the spread of "high- and low-temperature" plagioclase curves. These workers have determined the optical-crystallographic relationships of plagioclase from the same samples, obtaining independently the same relative scatter. Marfunin states that "Scattering of optical orientation data of natural plagioclases seems to be a result of insufficient precision. . . . " (1962, p. 299). This is disproved by the observation that scatter of optical-crystallographic orientation occurs only in specific rock types and not in others.

Rock Types

As far as possible, common volcanic, plutonic and metamorphic rock types were used in this study. The principal sources of sampal were 170 samples donated by Dr. R. C. Emmons, of the University of Wisconsin, which included 32 analyzed samples (Emmons, 1953, p. 16). Other important sources of samples were the petrology collection at the University of Wisconsin, which contains over 1500 samples, and numerous samples donated by colleagues.

The data presented below is not inclusive of all determinations made in this study. These samples were selected as being representative of broad classes of rocks, and illustrating the characteristic optical-crystallographic scatter of these rock types. Table 1 is a summary of the samples used for the examples and illustrations in this paper.

Methods of Optical-Crystallographic Orientation

Plagioclase twinning was studied in thin section by the five-axis method of plagioclase study as outlined by Emmons (1943). The general procedure used, in brief, is as follows: One unit of the twin is oriented optically and the positions of α, β and γ are determined. The composition plane is made vertical and north-south, and the pole to this plane is plotted stereographically in relation to the optical orientation. The alternate twin unit is then oriented optically and the composition plane is again made vertical; the pole of the plane is plotted stereographically in relation to the optical orientation. If the units are in twinned relationship, and are identical in optical properties, the plots of adjacent lamellae will coincide. If the poles do not fall within 3 degrees of each other and the original determination cannot be repeated within the allowable error the determinations are discarded. The only criterion used in the selection of grains for study is the ability to repeat the orientation within $1\frac{1}{2}$ degrees.

Precision of optical orientation was checked with a Nakamura plate used with a slotted ocular. This plate is a refined bi-quartz wedge and is used in the same manner. With this accessory, extinction positions can be

TABLE 1. SAMPLE DATA

Sample No.	Rock Type	Donor	Location
FD-24	Anorthosite	R. C. Emmons (1953, Sample 9)	Essex Co., N. Y.
FD-59	Gabbro	R. C. Emmons	Leesburg, Va.
FD-60	Monzonite	R. C. Emmons	San Juan Co., Colo.
FD-152	Gneissoid granodiorite	R. C. Emmons	Spanish Rock, Plumas Co., Cal.
FD-164	Troctolite	R. C. Emmons	Merrill, Wis.
FD-166	Troctolite	R. C. Emmons (1953, Sample 27)	Merrill, Wis.
FQ-1	Anorthosite	Petrology Coll., Univ. Wis.	Beaver Bay, Minn.
FQ-14	Olivine Basalt	Petrology Coll., Univ. Wis.	Mt. Etna, Sicily
B-24-15	Andesite	Petrology Coll., Univ. Wis.	Salz, Germany
N-19	Amphibolite	N. I. Christensen	Torrington Quad., Conn.
H-1-300-3	Norite	E. N. Cameron	Bushveld Complex, South Africa
M-1, 2, 3	Rhyolite	Mona Carpenter	Near Fairbanks, Alaska
A-8-1	Amphibolite	W. A. Dollase	Near Annie Lake, southern Ontario
V-9, 17, 26, 37	Qtz.-plag.-biot. gneiss	T. A. Vogel	Cornwall Quad., Conn.
V-15	Plag.-biot. gneiss	T. A. Vogel	Cornwall Quad., Conn.
T-3C	Anorthositic gabbro	T. A. Vogel	Tigerton, Wis.

determined to 0.1 degrees (Hallimond, 1953). Its use in universal stage orientations is explained by Vogel (1964).

RESULTS OF INVESTIGATIONS

Internal scatter. Two types of optical-crystallographic scatter are recognized in this study: internal and external. Internal scatter is defined as the scatter of the plots (either poles or twin axes) of adjacent lamellae within a single grain. When adjacent units of a twinned grain are oriented individually and are identical optically, the plots of their poles should coincide. Internal scatter occurs when these plots do not superimpose. By definition then, adjacent lamellae which show internal scatter are not in a true twinned relationship.

Internal scatter is random relative to the migration curve, and it is common that one unit may plot on or near a migration curve and the other unit be completely irrational. Frequently only a few grains in each sample will show internal scatter. It is important to identify internal scatter for it can mask the petrogenically more significant external scatter.

Figure 1 is a typical x-ray precession photograph of a grain that exhibited internal scatter. The b^* and c^* axes doubled and are not symmetrically disposed over both sides of the photograph. Six precession photographs were taken of grains that contained internal scatter and all were similar in appearance to that of Fig. 1A. Figure 1B is a similar appearing precession photograph produced by taking two different exposures of an untwinned grain. Between each exposure the crsytal was slightly rotated and translated. The results are nearly indistinguishable from the twinned crystal that contains internal scatter. This demonstrates that adjacent lamellae of plagioclase grains which show internal scatter are not in a true twinned relationship.

Electron probe analyses were made on four grains that displayed internal scatter. (All electron probe analyses were made at the University of Chicago by Dr. J. V. Smith.) The first determination was on a plagioclase grain from an amphibolite from northwestern Connecticut (Sample N-19). One lamellae of the grain plotted optically as a (001) twin with a composition of An_{26}, and the other lamellae plotted completely irrational. The electron probe analysis indicated that there was a difference of five per cent anorthite between adjacent lamellae. This difference in composition between the adjacent lamellae cannot account for the large internal scatter observed optically.

The second and third electron probe analyses were made on grains from Sample FD-24. The second analysis was made on a grain that contained a large simple twin with an internal scatter of eight degrees, and

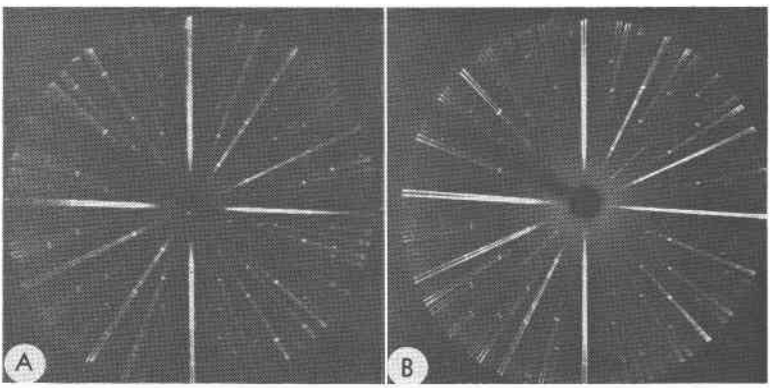


FIG. 1. A. Typical precession photograph of a twinned grain that exhibits internal scatter. Doubled b^* and c^* axes are present and are asymmetrical.

B. Precession photograph of an untwinned grain. Asymmetrical doubling of the b^* and c^* axes was artificially produced by taking a double exposure. Between each exposure the grain was slightly rotated and translated.

the poles plotting near the (001) migration curve. The electron probe analysis indicated that there was no difference in composition between adjacent lamellae.

The third determination was made on a grain that exhibited regular, evenly spaced polysynthetic twinning with (010) as the composition plane. A small internal scatter was noted parallel to the migration curve. The electron probe analysis indicated that one set of lamellae had a composition approximately two per cent higher in anorthite than the other set.

The last analysis was made on a grain from Sample V-37. The poles of the adjacent lamellae of this polysynthetically twinned grain plotted near the (010) migration curve, and the internal scatter was about thirteen degrees. The electron probe analysis indicated that there was no difference in composition between adjacent lamellae.

Internal scatter may be present in all twin types from all environments, and is random relative to the migration curve. Optical and x-ray methods indicate that grains that contain internal scatter are imperfectly twinned.

External scatter. The most petrogenically important type of scatter is external scatter, which is the scatter of the plots, either poles or twin axes, between different grains within the same sample. For example, two twinned grains in the same sample may exhibit no internal scatter, but the plots of these individual grains show the more significant external scatter. Grains that contain internal scatter are not used in studying external scatter.

External scatter is confined to certain rock types and is absent in others. In volcanic and metamorphic rocks, external scatter is entirely parallel to the migration curves, whereas in coarse-grained, igneous-appearing rocks the scatter is random.

In samples of definite volcanic origin the external scatter is negligible except in directions parallel to the migration curve. Figure 2 exhibits the external scatter of three typical volcanic plagioclases, and is representative of the external scatter in this genetic rock type. The volcanic samples fall on or near the disordered curve for plagioclase, and they illustrate the principle that volcanic rocks exhibit relatively little external scatter normal to the migration curve.

Rock types of definite regional metamorphic origin contain little external scatter in directions normal to the migration curves. Figures 3A and 3B exhibit the typical external scatter which is representative of metamorphic rocks. The (010) and (001) samples on these diagrams are from regionally metamorphosed argillaceous sediments (almandineamphibolite facies) of northwestern Connecticut. The pericline samples are from an amphibolite interpreted to be a product of regional metamorphism of a calcareous sediment in southern Ontario (W. A. Dollase, pers. comm., 1962). These samples display little external scatter and are from definite metamorphic rocks.

External scatter is present in a variety of samples, but is almost universally present in coarse-grained, igneous-appearing rocks such as gab-

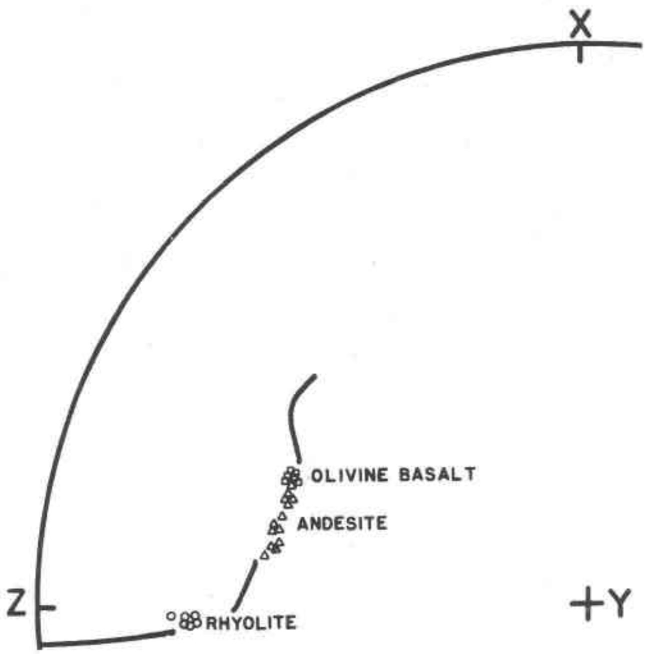
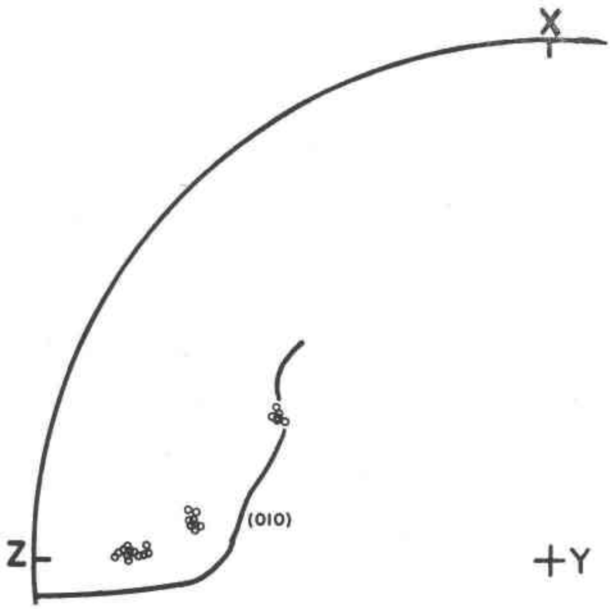


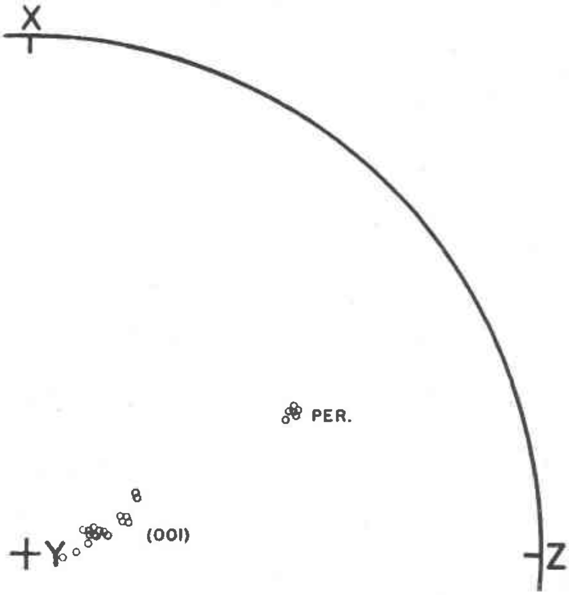
FIG. 2. External scatter typical of plagioclase from volcanic rocks. The disordered migration curve is drawn for reference. (Olivine basalt, FQ-14; andesite, B-24-15; rhyolite, M-1, 2, 3; Table 1).

bro, anorthosite, norite and pyroxenite. One boundary of this scatter approximates the "high-temperature" curves of Van der Kaaden (1951), but the other boundary continues beyond his "low-temperature" curve. Often the external scatter of an individual sample may completely bridge the gap between the "high- and low-temperature" curves. This is illustrated in Fig. 4 which is a plot of the typical external scatter of plagioclase from representative coarse-grained, igneous-appearing rocks. Figure 5 is a compilation of the external scatter for the (010) poles for all the samples studied. The boundaries of the scatter are well defined.

External scatter in Carlsbad and albite-Carlsbad twins within a sam-



3A



3B

FIGS. 3A and 3B. External scatter typical of plagioclase from regionally metamorphosed rocks. The disordered migration curve for (010) is drawn for reference. (Samples V-9, 17, 26 plot nearer to the sodic end of the curve and are quartz-plagioclase-biotite gneisses. Sample V-15 plots near the calcic end of the (010) migration curve and is a plagioclase-biotite gneiss. The pericline twins are from sample A-8-1, an amphibolite.)

ple is negligible. Figure 6 exhibits the external scatter of the poles to the composition plane present in seven selected samples thought to be representative of the external scatter in these twin types. The great majority of points show little scatter normal to the migration curve within a sample. Scatter between samples, disregarding compositional differences, may be present and is represented by comparing samples T-3C and FD-59 in Fig. 6. Optically these samples have the same com-

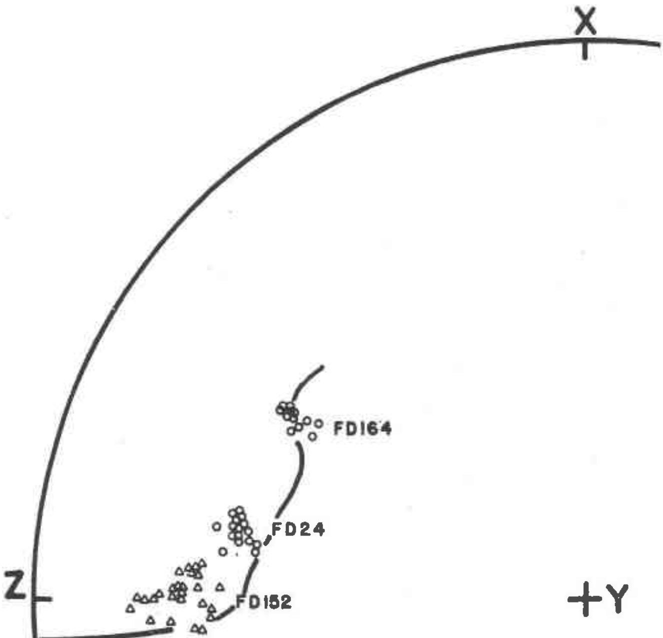


FIG. 4. External scatter typical of plagioclase from coarse-grained, igneous-appearing rocks. The disordered migration curve is drawn for reference. (FD-164, troctolite; FD-24, anorthosite; FD-152, granodiorite.)

position, but each individual sample plots at a different position—the scatter here is perpendicular to the migration curve. These diagrams illustrate a general principle of Carlsbad and albite-Carlsbad twins, that they exhibit little external scatter within a sample but may exhibit scatter between samples.

There is little external scatter associated with late-stage deformational twinning. These twins are related to crystal boundaries, fractures, imperfections, or to strain in the crystal and are usually lens-shaped. Figure 7 illustrates the plots of these late-stage deformation twins for a typical sample, and a comparison of these plots with the overall external scatter

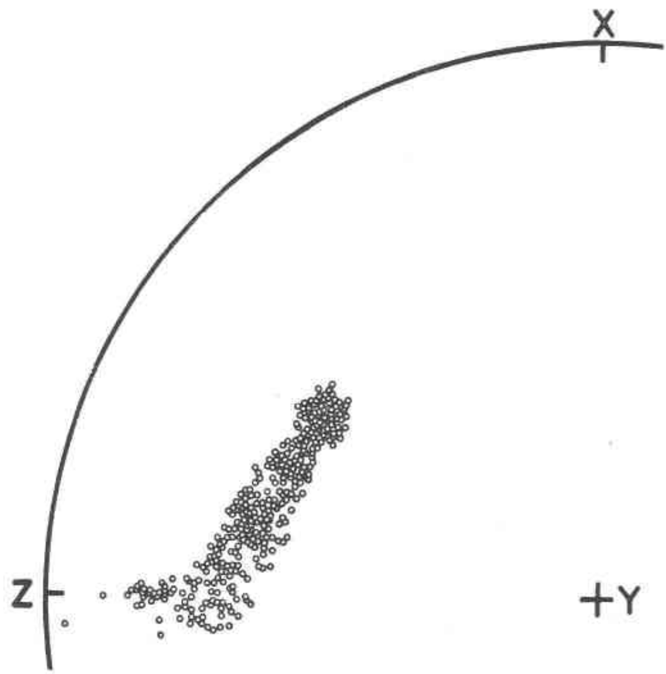


FIG. 5. Compilation of the external scatter for all (010) twins determined in this study.

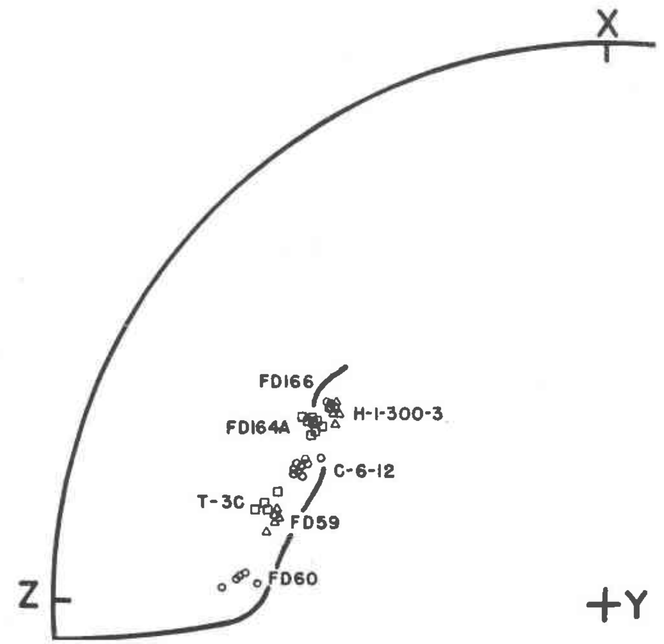


FIG. 6. External scatter typical of Carlsbad and albite-Carlsbad twins. Note that the scatter normal to the migration curve within an individual sample is negligible. (FD-59 and C-6-12, gabbro; FD-164 and FD-166, troctolite; H-1-300-3, norite; FD-60, monzonite; T-3C, anorthosite.)

in the sample is interesting. These late-stage twins plot near the outer extreme of scatter near the ordered migration curve.

The most important observations of external scatter are:

1) External scatter of volcanic samples is negligible and that which is present is confined to directions parallel to the migration curve.

2) External scatter in regional metamorphic rocks is also negligible and confined to directions parallel to the migration curve. Plots of metamorphic samples and volcanic samples of the same composition fall at different places on the stereogram.

3) There is no external scatter in Carlsbad and albite-Carlsbad twins within a sample, but there may be scatter between samples of the same composition.

4) External scatter of coarse-grained, igneous-appearing rocks is extreme and often

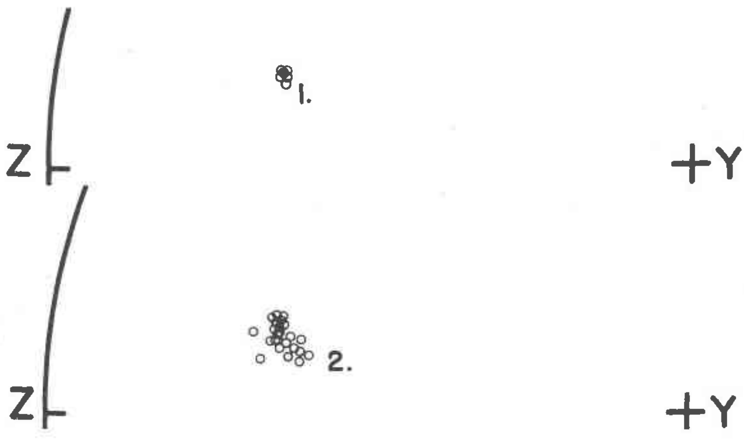


FIG. 7. External scatter of late-stage deformation twins (1), compared with the overall external scatter of the sample (2). (FD-24, anorthosite.)

covers the area between the classical "high- and low-temperature" curves. One boundary of this scatter approximates the "high-temperature" curve whereas the other boundary extends beyond the accepted "low-temperature" curve.

5) When late-stage deformation twins can be recognized, they exhibit negligible scatter.

The Origin of External Scatter

External scatter between grains within a sample is directly related to the genetic twin type and rock type. Growth twins show a type of external scatter different from deformation twins. Metamorphic, volcanic, and "plutonic" rocks all have their characteristic type of scatter.

The relationships between optical orientation and crystallographic elements is dependent on structural state as well as on composition of plagioclase. Plagioclase in the disordered state will have different optical-crystallographic relationships than plagioclase in the ordered state and plagioclase grains of different composition will also have different optical-crystallographic relationships, as shown by the characteristic migration curves. Twin elements depend on crystallographic elements, which are themselves dependent on the structural state and composition of the plagioclase. Volcanic samples plot on one migration curve and metamorphic samples on a different curve. The standard interpretation of this difference is that the volcanic rocks formed at high temperatures and the metamorphic rocks formed at low temperatures. The problem is that the coarse-grained, igneous-appearing rocks generally exhibit optical scatter that fully covers the spread between the "high- and low-temperature" curves.

The pericline twin illustrates the origin of external scatter. Pericline twins have the *b*-axis as the twinning axis and the rhombic section as the composition plane. The rhombic section is an irrational plane that contains the *b*-axis and intersects the (010) plane in a line normal to the *b*-axis (Smith, 1958). Its orientation is specified by giving the angle between the *a*-axis and the trace of the rhombic section on the (010) pinacoid. When the lattice angles are such that this angle equals zero, the pericline twin plane and the (001) plane are identical.

Smith (1958, p. 915) has suggested a reasonable explanation for the scattering in pericline twins. He states that

> "Although the rhombic section and the pericline composition plane, theoretically must be parallel when the twin lamellae are established, it is not necessary that they remain parallel, for the lattice angles, and hence the rhombic section, may subsequently change in response to structural and compositional changes, while reorientation of the compositional plane would involve such drastic movements of the feldspar lattice that it is unlikely that the adjustment could occur only upon recrystallization or perhaps under the influence of shearing force."

If a pericline twin forms in a disordered plagioclase and the plagioclase subsequently orders, the composition plane of the pericline twin, although parallel to the rhombic section at the time of formation, would not remain parallel; for as the structural state changes the position of the rhombic section also changes. Furthermore if pericline twins were forming at different stages during this structural change, these twins would all have a different position—parallel to the rhombic section only at the time of formation. External optical-crystallographic scatter is present *between samples* that have twinned at one state and are now at different structural states; and external scatter is present *within an individual sample* in which different grains have twinned at different stages in the ordering process.

Laves (1952) advanced the theory that twinning could occur in plagioclase only where the Si/Al-O framework was nearly or exactly monoclinic. In albite or intermediate plagioclase only the disordered plagioclase approaches the monoclinic form. The results of the present study indicate that twinning can take place at any structural state and that the external scatter observed within a sample is due to twinning during this ordering process.

It is well known that the crystallographic directions and angles upon which twinned elements are dependent change in response to structural transformations as well as to changes in composition (Ferguson *et al.*, 1958; Brown, 1960). The positions of all composition planes at the time of formation are controlled by the crystal structure, and except for the pericline twin, are parallel to rational crystallographic planes. As the structural state of the crystal changes these crystal planes must change relative to one another, for the crystallographic angles, on which they depend, change with the ordering process.

For example, albite twins are formed parallel to the (010) plane, but if the structural state of the crystal changes after the twin forms, the albite compositional plane is no longer parallel to (010). Other albite twins may form during and after this ordering process. Each albite twin, when formed would be parallel to the prevailing (010) plane, but would not be parallel to albite twins formed at a different structural state. Twinning can take place throughout the ordering process, thus producing external scatter if different grains are being twinned, and internal scatter if a single grain is repeatedly twinned during an ordering process. Figures 8 and 9 illustrate twinning that has taken place at different structural states within a grain thus producing internal scatter. Figure 8 is a photomicrograph of a large grain that contains a Carlsbad twin and many small albite lamellae. Theoretically both of these twins have the (010) plane as the composition plane, however the composition planes of the albite and Carlsbad twins in this grain are not parallel. The Carlsbad twin is probably a growth twin and formed in the disordered state, whereas the albite twins formed after the crystal ordered. Figure 9 exhibits two acline twins that are not parallel. Theoretically the composition plane of these twins should be parallel to the (001) plane, yet the two planes deviate from each other by about 4°. This deviation is probably due to the twins forming at different structural states.

If the twinning takes place while the plagioclases are in the disordered state, and no ordering takes place, there will be no external scatter normal to the migration curve. This is typified by volcanic rocks, in which the disordered structure of the plagioclase has been quenched or frozen and the samples show very little scatter (Fig. 2). Twinning in these samples took place at the same structural state; the plagioclase did not go through a structural change and therefore each twin has the same relationship to the optical orientation. No scatter is observed.

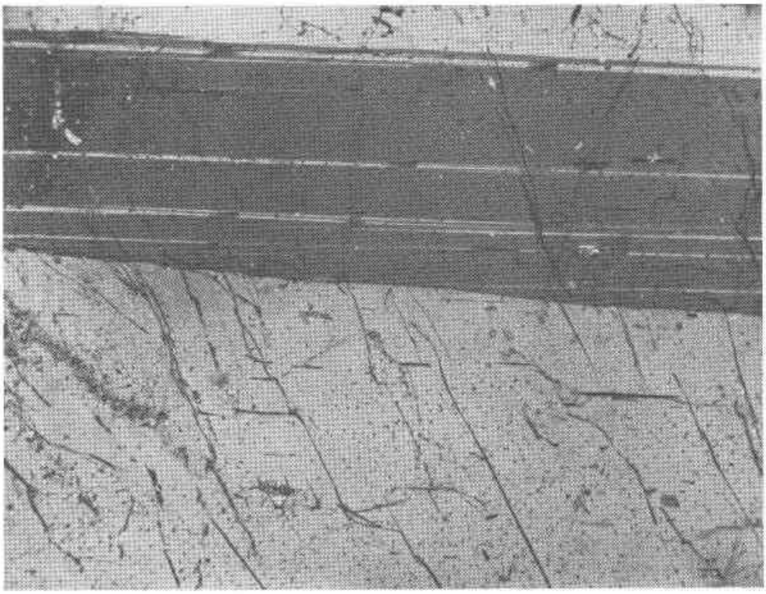


FIG. 8. Photomicrograph of a large grain which contains a Carlsbad twin and many small albite lamellae. Theoretically both of these twins have the (010) plane as the composition plane, however, the composition planes of the albite and Carlsbad twins in this grain are not parallel. (63×) (Sample T-3C).

Plagioclase that twin in the ordered state and remain in the ordered state will show no external scatter. The lack of scatter and the position of the plots of regional metamorphic plagioclase indicate that the twins formed when the plagioclases were fully ordered, and that they remained in the ordered structural state (Fig. 3).

Brown (1962, p. 360) suggests that growth of metamorphic plagioclases may take place by way of the disordered form. Long-continued deformation twinning that results from a high stress field during regional metamorphism may destroy any record of this disordered form. The present worker suggests that deformation twinning in plagioclase starts at crystal boundaries, imperfections or impurities and that the first twins to form are lenticular lamellae. This mechanism is similar to that observed in metals (Azároff, 1960, p. 158). As yielding continues the lamellae widen and the lenses continue across the crystal, straightening out as they reach the other side. Many lamellae coalesce to such an extent that the stresses cannot be maintained on an individual lamella and a new unit forms elsewhere in the crystal. The end product is a merging of nearly all the twins in the crystal with only a few thin, continuous lamellae remaining. In a sense, with continued yielding the crystal has become nearly untwinned and in this respect earlier twinning, some of which may have formed during a disordered or partly ordered state, is lost. Some metamorphic plagioclases are untwinned and may have gone through this twinning process, with a new result that many crystals are purged of twinning. This can explain the mysterious problem of those metamorphic rocks that were undoubtedly in a high stress field, but contain few twinned plagioclase. The prevalence of untwinned plagioclase in metamorphic rocks has been documented by Gorai (1951) and Turner (1951).

Extensive external scatter almost always occurs in coarse-grained, igneous-appearing rocks, and is confined to the area between the migration curves (Fig. 4). It is significant that in a single sample, the scatter can bridge the gap between the disordered and ordered migration curves. Coarse-grained, igneous-appearing samples contain scatter because the plagioclase grains have twinned at different stages during the ordering process.

Carlsbad and albite-Carlsbad twins are rare in a rock type definitely of non-igneous origin (Gorai, 1951; Turner, 1951). Many of these twins can be identified as growth twins by the criteria and features suggested

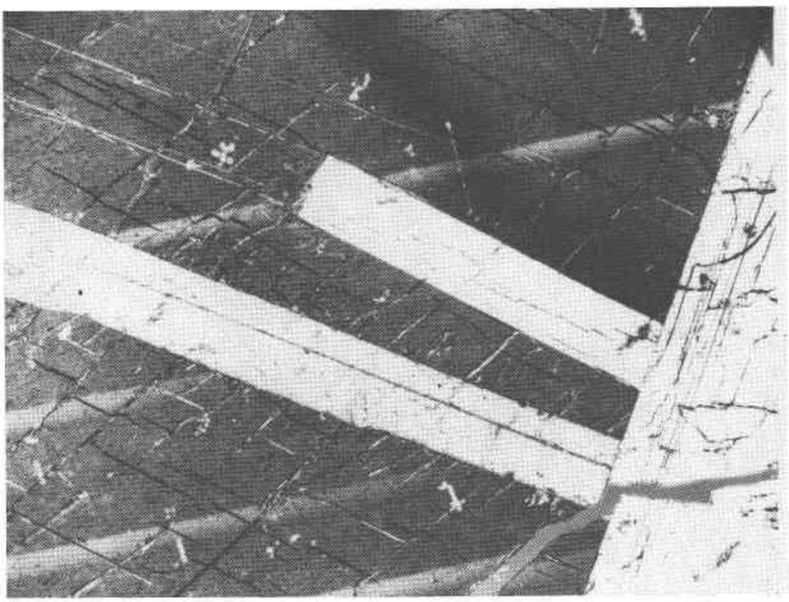


FIG. 9. Photomicrograph of a grain that contains two acline twins which are not parallel to each other. Theoretically, both of these twins should be parallel to the (001) plane, but the deviation here is about 4°. The other twins present in this grain are Carlsbad and pericline. (The shadow in the upper right corner is due to a scratch on the glass slide.) (63×) (Sample FQ-1).

by Vance (1961). These twins are usually simple, many are associated with a reentrant angle at the twin boundaries and show little external scatter within a sample. These factors lead to the conclusion that Carlsbad and albite-Carlsbad twins are growth twins. Buerger (1945, 1960) suggested that growth twins form at the time of nucleation. These twins would most likely be in a high energy, disordered state. The optical-crystallographic scatter of Carlsbad and albite-Carlsbad twins indicates that within a sample these twins formed at the same structural state. If the structural state has changed after formation of the twins, all of the growth twins within a sample have gone through the same structural transformation, and therefore the relationship between the composition plane and the optical orientation would all have changed the same relative amount. This results in negligible external scatter within a sample. However, external scatter between samples occurs because plagioclases from different environments have been through different ordering histories (Fig. 6). Although growth twins occur at the time of nucleation and would probably be disordered at the time of formation, the subsequent ordering history of growth twins from various environments would be reflected by the differences in scatter between samples.

When late-stage deformational twinning in plagioclase can be recognized, it shows very little external scatter. These twins formed at nearly the same period in the history of the plagioclase and at similar structural states. These points generally plot near the metamorphic plagioclase and indicate that the twins probably formed when the plagioclase was nearly fully ordered (Fig. 7).

The origin of internal scatter. Internal scatter is not as petrogenically important as external scatter because unquestioned interpretations cannot be obtained from it. Internal scatter may be of any magnitude and in any direction and is the result of an imperfect twin. It occurs in all twin types from all environments. Recognition of internal scatter is important for it can mask the more significant external scatter.

By definition, adjacent lamellae of grains that show internal scatter are not in a true twinned relationship. This may be caused by at least four distinct mechanisms. Internal scatter may be explained by twinning of an individual grain at different structural states, as established in the preceding section. The resulting scatter is confined to the area between the migration curves.

Muir (1955) has suggested that some internal scatter may be a result of different degrees of ordering between adjacent units. It is not yet possible to evaluate fully this mechanism as a cause of internal scatter. On the basis of the present state of knowledge on the ordering process, however, it would be unlikely that a single crystal would contain different states of ordering, for the factors that lead to ordering in one part of the crystal should also have operated on the other part.

Internal scatter can result from a difference in composition of contiguous lamellae. Compositional differences in adjacent twin lamellae have been recognized optically for many years (Emmons and Mann, 1953), and as much as 20 per cent difference in anorthite content has been noted. In the present study internal scatter parallel to the migration curves is common and generally reflects compositional differences. With this relationship in mind, the electron probe analysis described above (third analysis) was made on a grain that contained a small internal scatter parallel to the migration curve. The compositional differences that were determined with the probe were nearly identical with the differences observed optically. Although a complete study with the electron probe is indicated, the analysis demonstrated that compositional differences are real and can produce internal scatter parallel to the migration curves.

Internal scatter can result from an imperfection in the twinning process. This imperfection can take place at the time of formation of the twin or can result from distortion due to deformation and movement along the composition plane of a twinned crystal. This plane, being a zone of weakness, is a likely place for stresses to be absorbed. If these stresses are excessive, the planes may yield by rupture and may permit any amount of movement along the composition planes, thereby producing all degrees of internal scatter. Internal scatter occurs so ubiquitously that it must be explained by a mechanism that can be applied to all rock types and occurrences. This mechanism may be movement along preexisting composition planes.

Summary and Petrogenic Significance of Plagioclase Twinning

The principal emphasis of this study has been the relationship of optical-crystallographic scatter in plagioclase to the environment of formation of the rock type. The method has been to study samples from known environments to determine the optical-crystallographic relationships. A pattern in these relationships has been established and it is thought that this pattern can be used to make petrogenic interpretations about rock types from unknown origins. Scatter can be used as an interpretive tool in routine petrographic determinations.

Previous workers have averaged the scatter and produced one point as representative of a particular sample (Van der Kaaden, 1951; Glauser, 1961). If migration curves are based upon these averages it results in the scatter being distributed equally on both sides of the curves and the significance of the scatter is then lost. All external scatter should fall between the disordered and the ordered curves.

Interpretations based on the averaging of points are subject to grave errors unless the scatter is negligible. As has been brought out above, only growth twins and late stage deformation twinning can be used in deductions on the present structural state of the plagioclase in coarse-grained, igneous-appearing rocks. Late stage deformational twins, at best, give only the structural state at the time of formation of the twin. Glauser (1961) averages his points to determine the relative temperature of formation of the sample. In his samples 7, 9 and 10 he concludes that these are high-temperature (7) or intermediate-temperature (9, 10) based on the averaging of the scatter. The scatter of these points fully covers the range between the disordered and ordered curve, and there is no real significance to this average. Samples that exhibit a clustering of points within a broad overall pattern of scatter can be interpreted to have been subjected to severe twinning at a particular structural state, possibly at the time of intrusion, or due to some high level deformation during a structural change.

New disordered and ordered plagioclase migration curves are presented for the (010) poles in Fig. 10. These are based primarily on determinations made in this study, but also on some of Crump and Kettner's, and Glauser's work. Because of the composition range within a sample the compositions noted on these curves can be considered as only approximate. The curves more sodic than An_{30} have not been completely determined because of the lack of adequate samples in this range. All analyzed samples used in determining the compositions on the ordered curve came from Emmons (1953). The compositions on the disordered curve were approximated after Van der Kaaden (1951).

In establishing the ordered plagioclase curve, metamorphic samples were used whenever possible. If these were not available the curve was constructed on points that were furthest away from the disordered curve. This was done because in many samples this outer limit is often repeated, and also if metamorphic samples are available, they plot on or near this outer limit. The general trend of the curves is well established between An_{30} and An_{90}. Breaks in this curve may be present but information for the definite establishment of these breaks is lacking.

The disordered curve is very similar to Van der Kaaden's "high-temperature" curve and is based primarily on volcanic samples. This curve defines one boundary of the external scatter and the other boundary is defined by the ordered curve.

The cause of internal scatter is from imperfectly twinned grains and may result from various processes, the most important being movement along preexisting twin planes. Internal scatter of this type occurs in all twin types from all environments and is not of value for petrogenic interpretations. Internal scatter can also result from twinning of a grain at different stages in the ordering process and can often be recognized by the non-parallelism of the lamellae. Internal scatter results from differ-

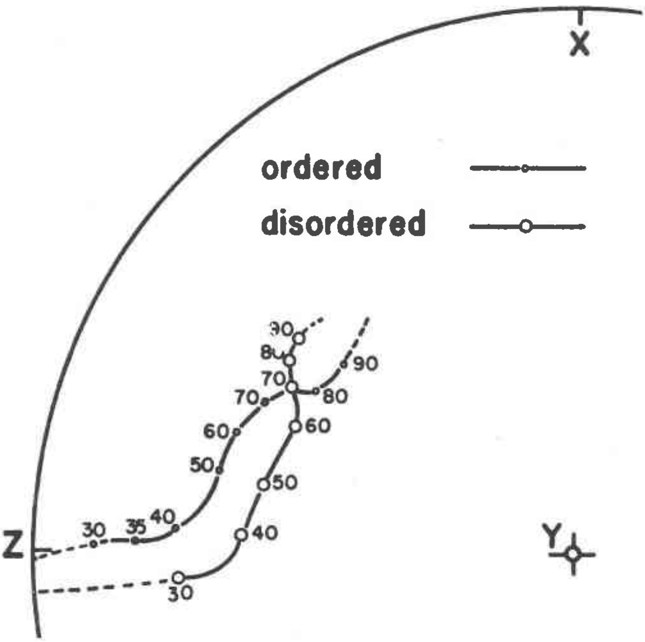


FIG. 10. New ordered and disordered migration curves for plagioclase. These curves define the boundaries of the external scatter of plagioclase determined in this study. The samples from metamorphic rocks fall on the ordered curve whereas samples from volcanic rocks fall on the disordered curve. The compositions noted on the ordered curve are based on Emmons' (1953) analyzed specimens. Because of the compositional range within a thin section, the compositions noted on this curve can be considered only approximate. The disordered curve is similar to Van der Kaaden's (1951) "high-temperature" curve and some compositions were approximated from his curve.

ences in composition of adjacent lamellae, and results in scatter parallel to the migration curves. It is important to identify and separate the internal scatter for it can mask the more significant external scatter.

The most petrogenically revealing type of scatter is external scatter, and it is the optical-crystallographic scatter between different grains. Grains that contain internal scatter are not used in studying external scatter. Most volcanic and regional metamorphic samples show only compositional scatter and contain no external scatter normal to the migration curves. The plots of these samples define the disordered and ordered migration curves for plagioclase. Coarse-grained, igneous-appearing rocks almost always contain external scatter, and this scatter is confined to the area between the migration curves. It is significant that in a single sample the scatter can bridge the gap between the disordered and ordered migration curves.

External optical-crystallographic scatter is present between samples that have twinned at one state and are now at different structural states. External scatter within an individual sample is due to twinning of different grains during the ordering or disordering process. Most volcanics do not contain external scatter because the samples formed, twinned, and remained in the disordered state. Similarly, no external scatter occurs in most regional metamorphic samples because they also twinned and remained at a specific structural state—the ordered state. Coarse-grained, igneous-appearing samples exhibit scatter because they have twinned throughout the ordering process.

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References

Azároff, L. V. (1960) *Introduction to Solids.* McGraw Hill Book Co., Inc., New York.

Brown, W. L. (1960) Lattice changes in heat-treated plagioclases. *Zeit. Krist.* **113,** 297–329.

——— (1962) Peristerite unmixing in the plagioclases and metamorphic facies series. *Norsk Geol. Tidssk.* **42,** 354–382.

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

——— (1960) Twinning with special regard to coherence. *Cursillos Y Conferencias Inst. "Lucas Mallada,"* **7,** 5–7.

Crump, R. M. and K. B. Kettner (1953) in, Emmons, R. C., ed., Selected petrogenic relationships of plagioclase. *Geol. Soc. Am. Mem.* **52,** 23–38.

Emmons, R. C. (1943) The universal stage. *Geol. Soc. Am. Mem.* **8.**

——— (ed.) (1953) Selected petrogenic relationships of plagioclase. *Geol. Soc. Am. Mem.* **52.**

Ferguson, R. B., R. J. Traill and W. H. Taylor (1958) The crystal structures of low-temperature and high-temperature albites. *Acta Cryst.* **11,** 331–349.

Glauser, A. (1961) Zur Orientierung der Indikatrix im Plagioklas-Material von R. C. Emmons. *Schweiz. Mineral Petrog. Mitt.* **41,** 443–470.

Gorai, M. (1951) Petrological studies on plagioclase twins. *Am. Mineral.* **36,** 884–901.

HALLIMOND, A. F. (1953) *Manual of the Petrographic Microscope.* Cooke, Troughton, and Simms, Ltd., York, England.

KÖHLER, A. (1941) Die Abhangigkeit vom vorangegangenen Wärmeverhalten. *Tschermaks Mineral. Petrog. Mitt.* **53,** 24.

MARFUNIN, A. S. (1960) Derivation of diagrams for the optical orientation of acidic and intermediate plagioclase. *Akad. Nauk. SSSR, Izvestiya, Geol. Ser.* (in transl.), **5,** 74–87 (pub. 1961).

——— (1962) Some petrological aspects of order-disorder in feldspars. *Mineral. Mag.* **33,** 298–314.

MUIR, I. D. (1955) Transitional optics of some andesites and labradorites. *Mineral. Mag.* **30,** 545–568.

NIKITIN, W. (1936) *Die Fedorow-Methode.* Gebrüder Borntraeger, Berlin.

REINHARD, M. (1931) *Universaldrehtischmethoden*, Basel, Wepf.

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.

TURNER, F. J. (1951) Observations on twin laws commonly exhibited by plagioclase in metamorphic rocks. *Am. Mineral.* **36,** 581–589.

VAN DER KAADEN, G. (1951) Optical studies on plagioclase feldspars with high- and low-temperature optics. Univ. Utrecht, Ph.D. Thesis.

VANCE, J. A. (1961) Polysynthetic twinning in plagioclase. *Am. Mineral.* **46,** 1097–1110.

VOGEL, T. A. (1964) The use of the Nakamura plate in universal stage orientations. *Am. Mineral.* **49,** 406–408.

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