GENETIC ASPECTS OF TWINNING IN FELDSPARS

By

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Introduction

As requested by the Advanced Study Institute of Feldspar, this paper will contain a review of some genetic aspects of feldspar twinning. In addition I shall make some original comments and suggestions on this subject with the aim of stimulating further research in the area. This paper will consist of three topics: the significance of twinning in microcline, the effect of structural state on the rhombic section and composition plane of pericline-twinned plagioclase, and some petrologic factors that affect the frequency and type of twinning.

I have profited greatly by extensive discussion with Professor Julian R. Goldsmith, to whom I wish to express my thanks.

Twinning in microcline

Laves (1950) in his important clarification of the properties of potassium feldspars found that cross-hatched microcline always revealed on X-ray photographs a special orientation between the two albite-twinned components, A_1A_2, and the two pericline-twinned components, P_1P_2, such that the (010) twin plane of the albite twins was perpendicular to the [010] twin axis of the pericline twins (this combination was later called an M–twin by Smith and MacKenzie). He pointed out that (010) is not perpendicular to [010] in triclinic material, and that it was necessary for M-twinned triclinic microcline to inherit this crystallographic relation from a monoclinic phase. His suggestion that cross-hatched microcline had formed by a transition from a monoclinic form was supported by the discovery of structural states intermediate between maximum microcline and monoclinic K-feldspar and of specimens containing both monoclinic and triclinic K-feldspars in which the albite and pericline twin elements were parallel to the (010) and [010] symmetry elements of the monoclinic material (Goldsmith and Laves (1954a,b) MacKenzie (1954) for example). As orthoclase is the most obvious monoclinic material from which microcline could form, it has become accepted by many scientists that the occurrence of cross-hatched microcline in a rock indicates a transition from orthoclase (which might itself have formed from sanidine). (In this paper orthoclase and sanidine are used in the sense of a petrologist, being characterized by the optic axial angle: the term sanidine was used by Laves and Goldsmith to mean a monoclinic K-feldspar and could include material here described as orthoclase).

Not all microcline occurs in the cross-hatched form. There is a considerable amount of sub-microscopically twinned microcline occurring in orthoclase and microcline perthites, but here the X-ray photographs of those specimens containing both albite and pericline twinning reveal an M-twin relation. Goldsmith and Laves ((1954b) p. 114) record the occurrence of untwinned microcline with triclinic morphology as an overgrowth on cross-hatched microcline from Ivigtut. They also record that Makinen and Eskola have described microcline perthite from Finland that is predominantly untwinned. In recent years, Marmo (1955a) has recorded in rocks from Sierra Leone microcline that is untwinned except for thin patches of cross-hatching, and has suggested that this microcline was primary.

Smith and MacKenzie (1954, 1959) and MacKenzie and Smith (1955, 1962) have found that in some perthites the triclinic K-phase occurs as two components related by a "diagonal association." If b-axis oscillation X-ray photographs are taken, pericline twins yield pairs of reflections on layer lines, while on b^*-axis oscillation photographs, albite twins yield pairs of reflections on row lines. In an M-twin, where b (pericline) is parallel to b^* (albite), sets of four reflections nearly at the corners of a parallelogram are obtained. In the diagonal association, only two reflections occur, falling on the sides of the parallelogram that lie on lines of constant θ (Figure 1). Thus in the diagonal association the two components occupy angular positions intermediate between those for the albite- and those for the pericline-twins of the M-association. The first example of diagonal association

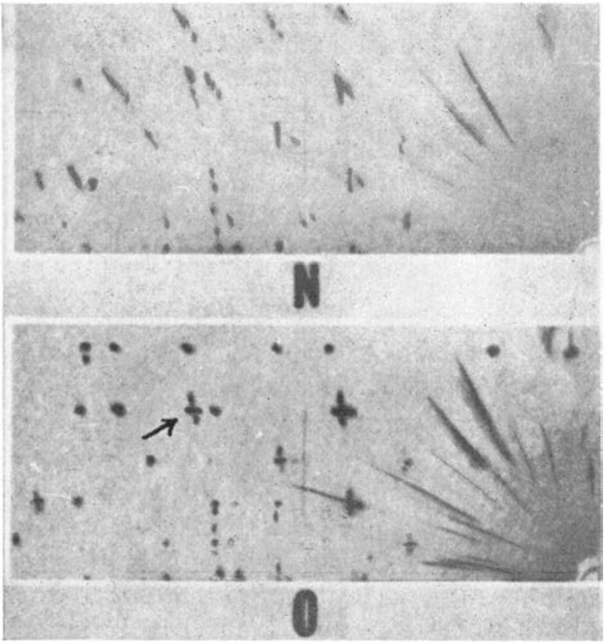

Figure 1. X-ray photographs of M-twinned and diagonal-associated feldspars. The upper and lower parts are for specimens Spencer N and O. Each part is one-quarter of a 15° oscillation photo taken with morphological b as the oscillation axis and with (001) in the center of the oscillation. In the lower photograph groups of four reflections can be seen (the group marked by the arrow is the most obvious). Two of the reflections lie east-west along a layer line while the other two lie along a row line. The marked reflections are for the (442) reflections of an M-twinned sodium-rich phase. The potassium-rich phase is monoclinic and is represented by single reflections adjacent to the groups of four. In the upper photograph the sodium-rich phase is only albite-twinned. The potassium-rich phase is partly monoclinic and partly triclinic. The triclinic part is represented by two reflections lying one on each side of the reflection for the monoclinic component. These two reflections lie in a diagonal position intermediate between the albite and pericline reflections of an M-twin (Taken from Figure 3 of MacKenzie and Smith (1955)).

(specimen Spencer N) had its components exactly half-way between the albite and pericline orientations, but other examples have shown that the diagonal components can lie anywhere between albite and pericline twin positions.

Baskin (1956a, b) has shown that in authigenic triclinic K-feldspars (many authigenic K-feldspars are monoclinic), those which are both albite and pericline twinned occur as fourlings in which the components are separated by the (010) plane and a plane at right angles to (010) which is not specified (but might be the rhombic section). The angular relation between the four components was not determined by Baskin, but he did show in his plate 2*B* a print of an X-ray photograph from which it may be seen that the reflections occur in groups of four. The stronger pair of spots are in the diagonal association, and the weaker pair may also be in a diagonal association but are close to the positions of albite twinning.

The genetic significance of the diagonal association is not known and further investigation, especially of authigenic feldspars, is desirable. It should be determined whether perthites with the diagonal association show special optical properties, whether the rhombic section is a composition plane in the fourling authigenic crystals, and what is the angular relation of the four units. It is possible that strain between albite and pericline twinned units may cause the diagonal association. Many crystals which show the *M*-twin give X-ray photographs in which the reflections for the albite and pericline units are connected by streaks. Such streaks must represent material in an intermediate position, presumably lying at the contacts of the twinned units. In addition, many photographs of perthites show the sodium-rich phase in angular positions which deviate slightly from those of true albite or pericline twinning. It is known that the angular orientation between the sodium- and potassium-rich phases of a perthite is governed by strain caused by mis-fit of the cell dimensions (Laves (1952a) Smith (1961)). It is suggested that the action of strain between the twin lamellae probably causes the small deviations from true pericline and albite twin positions in those specimens where both albite and pericline twins occur. It is possible that strain is also important when the triclinic K-phase occurs only as the diagonal association. Study of a stereographic projection (Smith and MacKenzie (1959) Figure 3) shows that the maximum angular mis-fit between the two components of the diagonal association is less than that for either albite or pericline twinning. Perhaps the diagonal association forms under special conditions for which it is especially important to reduce the strain between the components.

Another interesting question concerns the type of twinning to be expected during the microclinization of plagioclase, a process for which there is good petrological evidence in certain Pre-Cambrian rocks (e.g. Marmo (1955a)). Laves (1951) produced untwinned microcline (though with some mosaic distortion) by heating a single crystal of low albite coated with a glass powder of $KAlSi_3O_8$ composition. In the diffusion zone the extinction angle moved gradually from the value characteristic of low albite to that characteristic of microcline. Many investigators have shown that K and Na atoms move relatively freely in heated perthites. Thus it appears that if albite crystals undergo microclinization in a rock, microcline should be produced which will inherit the framework of the albite, unless the whole rock recrystallizes. As albite is commonly untwinned, this process should lead to the formation of untwinned microcline: if the albite is twinned the microcline should inherit the twin laws of the albite.

Ion-exchange of Ca-bearing plagioclase cannot take place so easily because of the charge linkage between the Ca + Al and the Na, K + Si atoms. Thus microclinization of oligoclase must involve the framework as well as the large cations, and microcline can only form from oligoclase by break-up of the framework, and migration of Ca. Consequently the microcline should not inherit the twinning of oligoclase. It is interesting to speculate on the type of twinning to be expected in the microcline. It seems likely that microclinization will proceed in a patchy manner with the K ions moving most easily through cracks and lattice dislocations. At many places, small nuclei of K-feldspar should form and it seems likely that these will contain disordered Al and Si atoms because of the disturbing nature of the surface forces when the nuclei are very small. As the nuclei grow larger, the incoming Al and Si atoms may continue to adopt a disordered configuration producing a monoclinic K-feldspar: alternatively the incoming atoms may adopt an ordered configuration producing microcline directly. Thus in the former case, microcline could only form by annealing from crystals that had first formed with a monoclinic structure, while in the latter, only the nuclei would not have grown directly as microcline. In both, cross-hatching should occur, for the microcline would inherit the symmetry elements of either the macroscopic or the microscopic units as twin elements. The coarseness of the cross-hatching would depend on the frequency of formation of the nuclei.

In some feldspar-bearing rocks there is evidence of recrystallization under the action of stress and one may ask what effect this will have on the twinning. Untwinned crystals have lower free energy than twinned ones, because of the energy in the twin boundary: however, most twins persist indefinitely because there is not enough activation energy available to overcome the large energy barrier for destruction of the twin boundaries. Shear stress should help in removal of twin boundaries, but only, it seems, if the stress does not exceed the mechanical limit of the crystal. If the crystal is shattered mechanically, recrystallization should take place and this might produce a metastable phase. Thus it is possible that shearing stress might produce either untwinned microcline or orthoclase from a twinned microcline. The orthoclase might later invert to a twinned microcline.

Evaluation of these possible phenomena can only be obtained after carefully controlled laboratory experimentation, and further detailed study of feldspars in well-described geological areas. Because of the need to meet the deadline for the conference, the author has no time for study of these problems, but he intends to follow them up with Professor Julian Goldsmith.

For the moment, it will suffice to discuss the data found by Marmo (1955a) in the granitic rocks of Sierra Leone. The majority of the microcline crystals in these rocks are beautifully cross-hatched, but the microcline of the pegmatites is untwinned except for thin streamers of cross-hatched microcline. Marmo presents excellent evidence in the plates for microclinization of oligoclase. In the non-pegmatitic material the original plagioclase was oligoclase and complete recrystallization was necessary. The microcline could have become cross-hatched either from disordered nuclei or from an intermediate monoclinic phase. Marmo states that there are inclusions of low albite ($2V \sim 76°$) in the pegmatitic microcline. Thus it seems reasonable to suppose that the microcline in the pegmatite formed by ion-exchange from albite, and did not need to become cross-hatched because there was no intermediate monoclinic phase. Marmo has suggested that the thin streamers of cross-hatched microcline might have been caused by stress. I am indebted to Miss Mabel Corlett for the suggestion that these streamers might have been oligoclase. Another possibility is that the albite might have been perthitic, and the streamers are formed of original K-feldspar.

Marmo thought it unlikely that any of the microcline had formed by ageing of orthoclase because of the absence of any residual orthoclase. He suggested (p. 166) that "in pegmatites the growing of the microcline is probably much more "free" than in other instances considered in the present paper. In the case of the replacement, the introduction of potassium into the lattice of plagioclase evidently must surmount certain frictional and structural resisting powers causing the grating from the very beginning of the formation of the microcline as also in cases of formation of interstitial microcline. Consequently the grating may be lacking only if there are no hampering factors present, as is the case only in the formation of pegmatites. But even there, if any stress or shearing or strain takes place, the grating will be developed." Laves (1955) criticized the views of Marmo for various reasons, and reiterated that cross-hatched microcline must have formed by inversion of a monoclinic feldspar, and could not have formed directly as a triclinic feldspar. Marmo (1955b) in his reply pointed out that there was petrographic evidence (cross-hatched porphyroblastic microcline without any trace of orthoclase; aplite dykes carrying cross-hatched microcline cutting orthoclase-bearing granulites; absence of orthoclase in microclinized rocks) that was not consistent with the formation of microcline via orthoclase. He wondered whether it would be possible for microcline to become cross-hatched if orthoclase formed in initial stages of growth, perhaps as single molecular cells. However, it is not clear what is meant by a single molecular cell. It cannot be a unit cell: perhaps a growth nucleus containing a large number of unit cells was in Marmo's mind. A further discussion bearing on the petrologic aspect of the problem is by Schermerhorn (1961) and Marmo (1961).

Another factor that will influence the formation of microcline is the presence of ferric ions replacing aluminum in the tetrahedral framework. Wones and Appleman (1962) have synthesized two varieties of $KFe^{3+}Si_3O_8$: one form is monoclinic, is stable above 700°C, and analogous to high-sanidine, and the other triclinic, stable below 700°C and analogous to maximum microcline. Transition between the two is rapid, unlike that between the Al-feldspars. Consequently it appears possible that Fe atoms in K-feldspars may form nuclei of microcline which will assist in the transformation of orthoclase to microcline.

In summary, there is considerable confusion about the nature and significance of twinning in K-feldspars. The basic idea proposed by Laves in 1950 is surely applicable to a great quantity of cross-hatched microcline, but further investigation is desirable of the possible effect of growth nuclei during microclinization, on the effect of shearing stress, and of the occurrence and nature of K-feldspars showing the diagonal association.

Rhombic section and pericline composition plane

This section of the paper will be quite brief for Smith (1958) has

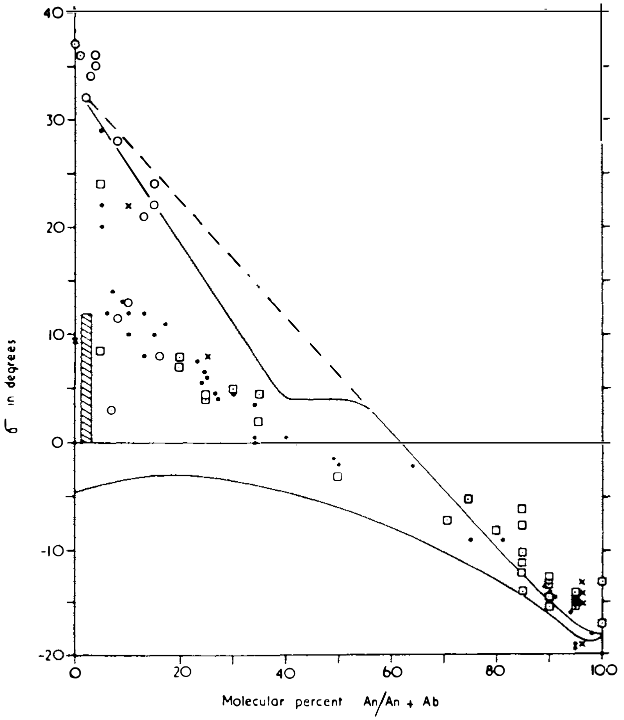

Figure 2. Comparison of σ values for the composition planes of pericline-twinned plagioclase feldspars with curves for the angles of the rhombic sections for the extreme high (lower curve) and low (upper curve) structural states of plagioclase. The dashed line is an extrapolation of the curve for calcium-rich feldspars in the low structural state and is of hypothetical significance only. The figure was copied from Figure 5 of Smith (1958). The measurements were collected from the literature covering a time span from 1894 to 1958: the sources of the data can be found from Smith (1958). Note how the majority of the values for the compositional range An_0 to An_{70} fall between the curves. Those for bytownite and anorthite deviate considerably, suggesting that the curves need revision for these compositions.

given a detailed account of the subject. The theoretical composition plane of pericline twins is the rhombic section, an irrational plane that contains the *b*-axis and intersects the (010) plane in a line normal to the *b*-axis. Its orientation is conveniently specified by the angle σ between the traces of the (001) cleavage and the rhombic section on the (010) pinacoid. The angle σ is a function of the cell angles and may be calculated from the relation $\cot \sigma = \cos \alpha^*/\cot \gamma$. Because α^* and γ are functions of both the chemical composition and the structural state of a plagioclase, it is possible for the rhombic section of a plagioclase to change either from metasomatism or from ordering of the Si,Al atoms. If the pericline composition plane remains unchanged during either of these processes, it will not agree with the rhombic sections. Thus there is the exciting possibility of demonstrating a change in the plagioclase subsequent to the formation of the pericline twin.

Figure 2 shows the theretical rhombic sections for plagioclase feldspars calculated from cell dimensions obtained at room temperature from feldspars in high and in low structural states. The calculated σ-angles are accurate for sodium-rich plagioclase, but are only estimated for the calcium-rich compositions. Superimposed on the diagram are many values for σ that had been recorded in the literature. Most of the specimens were from veins and pegmatites, and should be in the low structural state. However the majority of the σ-angles for the sodium-rich specimens indicate an intermediate structural state, thus suggesting that there has been a structural inversion or a change of composition towards albite. Laves and Schneider (1956), who had independently recognized the variability of the rhombic section, came to the conclusion from irregularity of the texture that the deviation between the pericline composition plane and the present composition plane of crystals of albite with the pericline habit had resulted from a compositional change from oligoclase. However it seems likely that some of the specimens shown in Figure 2, especially the more calcium-rich ones, have not changed composition, and that the deviation of the rhombic section and pericline composition plane is caused by a structural change.

Dr. Joseph Vance of the University of Washington has kindly allowed me to see a paper submitted to the Mineralogical Magazine in which he describes a zoned feldspar with both primary and secondary pericline twinning. Figure 3(*a*) shows how the two sets of twin lamellae

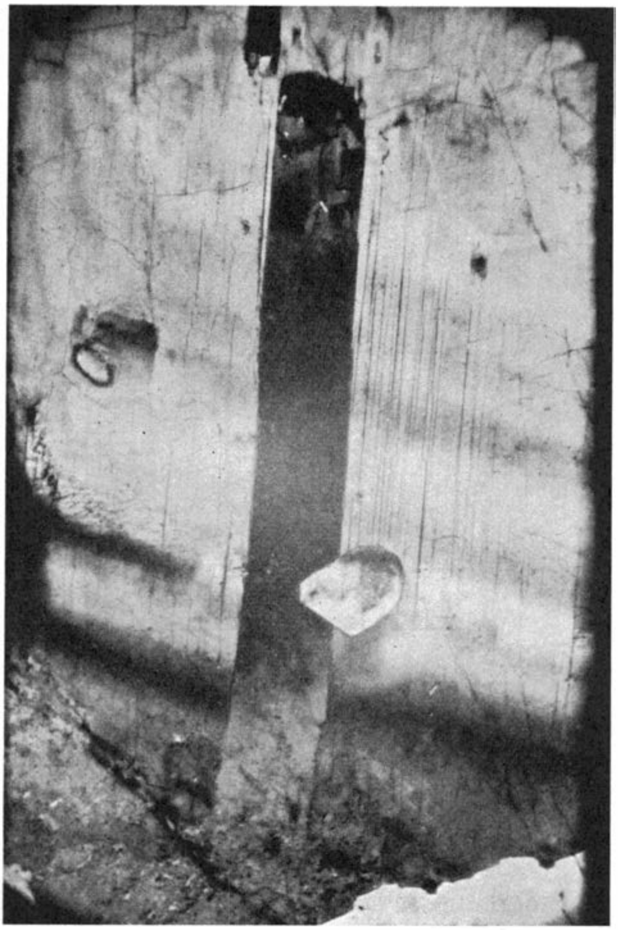

Figure 3. (*a*) Photomicrograph in crossed polars of a plagioclase crystal showing both coarse primary and fine secondary pericline twinning. Note how the angle of the composition plane changes in conformity with the zoning. (The fine pericline twinning is very hard to reproduce near the edge of the grain).

are related to each other, and how they change in sympathy with the chemical zoning: Figure 3(*b*) shows how the composition planes fit with the graph of calculated rhombic sections. It will be seen that the secondary twinning indicates a lower structural state than the primary twinning.

Dr. Ian Muir of the University of Cambridge has found pericline

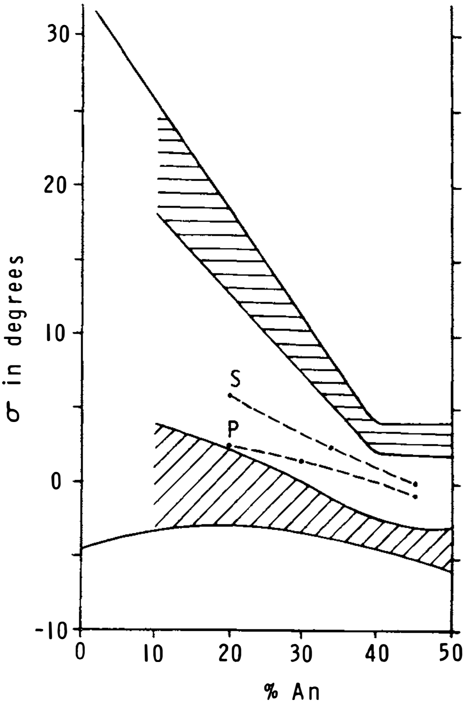

Figure 3. (*b*) Variation of the angle σ of the pericline composition plane with composition compared with the theoretical curves for the rhombic section. Note how the primary twinning gives σ-angles nearer to the high structural state than the secondary twinning.

This Figure was prepared from material kindly supplied by Dr. Joseph Vance.

composition planes of exsolved plagioclase in ternary feldspars from larvikites that indicate a high structural state, and were probably inherited from an anorthoclase. Dr. T. Donnelly of Rice University has found albites from volcanic rocks that are nearly in the low-temperature form, but have pericline twinning with a composition plane that fits with a high structural state. He has also studied anorthite from the Virgin Islands in which the coarse pericline twinning has a different angle from the fine polysynthetic lamellae. From the latter observations he believes the low-temperature rhombic section crosses the high-temperature rhombic section in the calcium-rich plagioclases. It is hoped that Drs. Muir and Donnelly will soon present details of their work.

Further study of the pericline composition plane, using the X-ray powder pattern to yield cell angles from which the rhombic section could be calculated, appears desirable. Results of petrologic significance should be obtainable.

Influence of petrologic factors on twinning in plagioclase

Twinning is the result of a special type of disturbance of the crystal structure either during or after growth: the energy in the twin boundaries of feldspars is relatively small so that twinning may have many different causes. Consequently it is very difficult to tie down the factors that cause twinning. Often resort must be made to tedious statistical studies which are subject to the possibility of mis-interpretation because a correlation may be either primary, secondary or the result of several factors working in combination.

First, let us look at the problem of deciding whether twinning is primary (i.e., formed at the time a crystal grew) or secondary (i.e., formed in the solid state after the crystal had formed). Vance (1961) has reviewed the literature and together with consideration of a considerable number of measurements of his own, has established criteria for distinguishing primary from secondary twinning. He concludes that primary twinning is usually single, with wide variations of thickness of lamellae, that lamellae change thickness abruptly and independently of neighboring lamellae, and are not related to fractures. Vance finds that secondary twinning in plagioclase is multiple with many fine lamellae, sometimes bent, often terminating at factures, and varying in thickness only a little and in the same fashion as neighbouring lamellae. He, like many previous investigators, attributes this type to glide twinning. Vance concludes from his own and other observations that none of the secondary twinning in plagioclase forms as the result of a structural transformation involving a change of symmetry (such as occurs in orthoclase going to microcline or sanidine to anorthoclase). However, I think that some of the plagioclase in the rocks from the Oslo area may have derived their twinning as a result of transformation of a single homogeneous ternary feldspar into a coarse perthite: but, I mention this with some trepidation in view of the much greater experience of our Conference hosts, and hope that they will discuss this at the Conference. It seems reasonable to me to conclude that secondary twinning in basic plagioclase and most acid plagioclase has formed as a result of stress, and only rare specimens with compositions near albite show transformation twinning.

Let us now assume that we can definitely distinguish between primary and secondary twinning, and proceed to study the factors that influence each.

Secondary (glide) twinning

As mentioned before, the most reasonable interpretation of this type of twinning is that it is caused by stress, Vance observed that in the same metamorphic terrain, glide twinning was distinctly less frequent in the finer-grained, more equant plagioclase than in the coarser, irregular material, and made the reasonable suggestion that the former crystals could rotate because they did not interlock, thus relieving the strain. Vance suggested that Gorai's observation (Gorai (1951)) that the frequency of twinning in metamorphic plagioclase varied with the grain size might be explained by a correlation between increasing grain size and a greater degree of interlocking. This suggestion should be tested.

Laves (1952b) in a short note, which he promised to amplify into a full paper, made a notable contribution in pointing out the control exerted by the Al/Si distribution in the feldspar framework on the ease of glide twinning. In low-albite, the Al atoms always occupy the same tetrahedral sites in the unit cell. Albite and pericline twinning of a single crystal involves the movement of all the Al atoms on one side of the twin boundary into one of the other three sets of sites previously occupied by Si atoms. Such a movement would be very difficult indeed because of the high strength of the tetrahedral bonds. In high-albite, the Si and Al atoms, being disordered, would give a monoclinic framework if the Na atom were large enough to fill the cavity and twinning did not occur (e.g., as in K and Ba feldspars). However the Na atoms move to one side or other of the cavity, distorting the framework, giving triclinic symmetry, and producing albite and pericline twinning. This process is displacive involving only a small energy barrier against the movement of the Na atom from one place to another in the cavity. Consequently glide twinning can take place easily in high albite, as was demonstrated by Laves by pressing a crystal of anorthoclase ($Na_{0.8}K_{0.2}AlSi_3O_8$) with a needle. (Movement of Na atoms also occurs in the twinning of low-albite but the Si,Al atoms provide the controlling factor).

In contrast to albite, anorthite is ordered at all temperatures, and because it has alternating Si and Al atoms in the framework (with a necessary 1:1 ratio of Si and Al), there is no change in the Si, Al distribution when albite and pericline twinning occur. Movements of Ca atoms from ideal positions provide the mechanism for the twinning (change of framework bond angles also take place) and consequently glide twinning of anorthite should occur easily at all temperatures. Indeed, Mügge and Heide (1931) produced glide twinning in anorthite quite readily.

Laves did not consider plagioclases with compositions between $NaAlSi_3O_8$ and $CaAl_2Si_2O_8$. Extending his conclusions, one finds that glide twinning in high plagioclase which has disordered Si,Al atoms can occur in all compositions without disturbing the pattern of Si,Al atoms. For low plagioclase the situation is not completely clear because the pattern of Si,Al atoms is not known for all compositions. In the peristerite range, An_0–An_{17}, two plagioclases, albite and oligoclase, coexist, and it seems that albite and pericline twinning would certainly involve movement of Si and Al atoms. In the range An_{17} to An_{75} a complex structure occurs which has been interpreted as a regular pattern of anorthite-like unit cells, partly replaced by cells with the composition of albite (Megaw (1960)). It seems certain that albite and pericline twinning would involve movement of Si and Al atoms. From An_{75} to An_{95} the situation is complex but again it seems likely that some of the Si and Al atoms would have to move. Thus there is a completely different situation at high and low temperatures for glide twinning in all plagioclase except anorthite. A further complexity is that all structural states between the extreme disordered and ordered states can occur, and it is not obvious what will happen when stress is applied to a plagioclase with partial Si,Al order. It is here suggested that glide twinning will occur so long as ordering has not proceeded over too much of the crystal so that there are not enough disordered regions of large enough size to permit the formation of glide lamellae. Ordered regions would resist the influence of shearing stress to change their orientation and one might end up with crystals showing irregular twin boundaries. Typical plagioclase twinning is sharply defined, but it is possible that irregular patchy twinning has been observed, but dismissed as an aberrant optical phenomenon.

Although no detailed studies of glide twinning throughout the whole plagioclase series have been made, those few investigations to date are consistent with the above picture. There are no reports of production of glide twinning in low plagioclase, except in anorthite, though it is likely that many investigators have tried. In contrast, heat-treatment of low and transitional plagioclase by Muir (1955) and others has resulted in fine secondary albite and pericline twin lamellae, presumably from the effect of stress during transition to a more disordered form.

It has been assumed implicitly that only a short time has been available for the application of shearing stress. Suppose, however, that shearing stress is applied for a long time, comparable to that required for the migration of a large percentage of the Si and Al atoms. Would this lead to the formation of glide twinning with regular lamellae? I think the answer is no, for such conditions would tend to produce a single crystal oriented in a way that would be least affected by the shearing stress. Intermediate states should probably give rather patchy textures.

Primary twinning

Vance has given a detailed account, based on the general theory of Buerger, of the factors that affect primary twinning. To summarize very briefly, primary twinning depends on the process of crystal growth itself and is affected by the composition of the external material, the rate of growth and the nature of the growing surface. Variations in these can be expected to occur frequently, thus explaining the irregular shape of primary twin lamellae. Vance observed that primary twinning is more common in euhedral than in anhedral plagioclase, and explains this on the basis that the energy of an irregular surface is higher than that of a regular surface and that it is unlikely that a further energy contribution from a twin boundary will occur. However I think that this may not be the only factor, for much of the euhedral plagioclase probably grows at a higher temperature than anhedral plagioclase, and a higher temperature should encourage twinning because of the greater thermal agitation.

One of the factors that should affect the frequency of twinning is the energy in the twin boundary. Donnay (1940) used the angle $b \wedge b^*$ as a measure of the energy and predicted the frequency of twinning from the variation of this angle with composition. Gay (1956) showed that $b \wedge b^*$ varied with structural state and Smith (1958) showed that the actual temperature at which twinning occurred probably had a larger effect than either of the other factors, making twinning more likely at the higher temperatures. Comparison with observations showed that this theory of structural control seemed to work quite well. However Vance correctly pointed out that much of the evidence was inadmissible because many of the observed twins were probably secondary glide twins. He states that his own observations of primary twins (presumably in gneissic rocks from the Cascades) showed no systematic variation between chemical compositon and lamellar width. However, he did not mention that Smith showed that the role of temperature seemed to be much greater than that of composition. Nor does he mention the evidence quoted by Smith from Oftedahl (1948) that in the volcanic rocks from the Oslo region the twinning of the plagioclase phenocrysts were very fine, and that specimens more sodic than An_{42} were optically monoclinic, indicating sub-microscopic twinning. In the plutonic rocks of the Oslo region the twinning, although still very fine, was somewhat coarser and the boundary between the triclinic and pseudomonoclinic specimens lay at An_{30}. Also van der Kaaden (1951) has noted that the frequency of twinning in volcanic rocks decreases markedly from oligoclase to calcic plagioclase. It seems likely that much of this twinning is primary, and if so, that structural control is of some importance for the primary twin in high-temperature plagioclase.

When we compare the following quotations from Turner (1951) Gorai (1951) and Vance (1961). it is clear that much careful observation and interpretation will be needed before it can be said that we understand in detail the formation of twins in plagioclase.

(1) Prevalence of untwinned plagioclase in metamorphic rocks of all types is too well known to merit further comment. There is scattered evidence in petrographic literature suggesting that twinning of plagioclase is more frequent in rocks of moderate to high metamorphic grade than in albite-bearing schists of the greenschist facies. Thus Phillips ((1930) pp. 244, 245) records increasing abundance of twinned

grains of albite in passing from the chlorite zone to the biotite zone of the Scottish Daldradian schists. My own observations confirm this general tendency....

(2) There seems to be no general correlation between abundance of twinning in metamorphic plagioclase and degree of deformation experienced by the enclosing rock....

(3) Various writers have contrasted the simple twinning of plagioclase in igneous rocks. (Phillips (1930) p. 27; Harker (1932) p. 213). In the great majority of metamorphic rocks which I have examined, twinned grains of plagioclase consist of few subindividuals and only one twin law is represented in most grains. This contrasts very strikingly with the variety and complexity of twinning exhibited by igneous plagioclase and with the large number of lamellae that occur in many grains in igneous rocks. There are, however, certain exceptions. In pyroxene granulites, and in certain hornfelses of relatively high grade, grains of plagioclase may consist of many closely-spaced lamellae, though there is still a marked tendency for only one twin law to be represented in any grain....

It seems likely that the differences noted above may reflect generally prevalent differences in the physical conditions of magmatic and metamorphic crystallization. It is possible, for example, that twinning behavior, as well as crystal habit and the nature of crystal boundaries, is affected differently by metamorphic crystallization of plagioclase in an essentially solid medium and by magmatic crystallization in a liquid medium. Temperature may well exert an even more important influence. Metamorphic temperatures in general are lower than magmatic temperatures...." Turner.

"It is noteworthy, moreover, that the frequency of twinned plagioclase... in these metamorphic rocks (schists and gneisses of amphibolite facies) has nothing to do with the average composition of the plagioclase, but depends on the average grain size of the plagioclase in each rock" Gorai.

"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'' Vance.

Relative frequency of twins

In conclusion, brief mention will be made of some studies which show that the relative frequency of twin types varies with petrologic environment. Gorai (1951) has described in detail the distribution of A-twins (albite, pericline and acline-A) and C twins (the remainder). He found that C twins are very rare in metamorphic rocks though a few occur, especially in the higher grade rocks. In igneous rocks, C twins are more frequent, and the percentage increases with the basicity of the rock and with the An-content of the plagioclase. Tobi (1961) reports that in medium-grade metamorphic rocks the pericline or acline law is often more frequent than the albite law, while the reverse is true for most magmatic rocks. In albite porphyroblasts of some low-grade metamorphic schists, the Carlsbad and albite laws are both found, whereas twins with composition planes other than (010) are rigorously absent. In spilites and trondhjemites, large number of Ala–A twins combined with albite lamellae may sometimes be found.

Further studies on these lines should prove of considerable value, both for petrologic purposes, and in determining the factors that cause twinning.

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