The effect of composition and structural state on the rhombic section and pericline twins of plagioclase felspars.

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Summary. The position of the rhombic section of plagioclase felspars, as calculated from the measured cell dimensions, has been shown to vary with the structural state, the variation from high- to low-temperature forms being most pronounced for albite. The theoretical composition plane of pericline twins is the rhombic section. If the structural state or the composition of the felspar changes after twinning has occurred, the cell dimensions and hence the rhombic section will change; however, the composition plane of the pericline twin will probably remain unchanged unless recrystallization occurs, or perhaps if the felspar is subjected to strong stress. Thus the observed pericline composition plane need not coincide with the rhombic section. Comparison of observed composition planes with the corresponding calculated rhombic sections shows that some of them do indeed differ and the differences have been used to provide information on the changes occurring subsequent to the establishment of the pericline twins. The interpretation is complicated by the occurrence of the acline-A twin, whose composition plane is {001}, for the rhombic section of plagioclase felspars from An_0 to An_{60} may coincide with {001} if the structural state of inversion has a particular value. When the observed composition would agree with both pericline and acline-A twinning, the new term *b-axis twin* has been used.

THE composition plane of the pericline twin, the rhombic section, has been the subject of many investigations over the past 120 years and it has usually been implicitly assumed that its orientation has been controlled by only one factor, the chemical composition. It is the purpose of this paper to show that the position of the rhombic section is mainly controlled by two factors, chemical composition and structural state.[1] Many interpretations of the observations on the pericline twin of plagioclase felspars are in conflict and it will be shown that these conflicts can be resolved when the effect of differing thermal history is considered.

Properties of pericline and acline-A twins.

Both pericline and acline-A twins are parallel twins with the *b*-axis as the twin axis: their respective composition planes are the rhombic

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[1] Called 'thermal state' in earlier papers on plagioclase felspars.

section and the (001) 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. Its orientation is conveniently specified by giving the angle σ between the *a*-axis and the trace of the rhombic section on the (010) pinacoid. When the lattice angles are such that $\sigma = 0°$, the pericline and acline-A twins are identical, a possibility of considerable practical importance. It is not possible to distinguish the pericline and acline-A twins by X-ray methods since diffraction of X-rays is not influenced by the composition plane. For these reasons, the noncommittal term *b-axis twin* is introduced for use when the twin axis but not the composition plane has been characterized.

Effect of structural and compositional changes.

Whereas the composition plane of the acline-A twin is a crystallographic constant and independent of physical variables, the rhombic section, being a function of the lattice angles, depends on the composition and the physical conditions. 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 re-orientation of the composition plane would involve such a drastic movement of the felspar lattice that it is likely that adjustment could occur only upon recrystallization, or perhaps under the influence of shearing force. If recrystallization occurred, the new composition plane would be controlled by the new rhombic section. The operation of shear forces might help to re-orient the lamellae, for Mügge (1930) has produced pericline twinning in anorthite by the application of shear force and Phillips (1929) has noted the prevalence of pericline twinning in low-grade metamorphic schists that have been subjected to stress. Structural changes resulting from the movement of Si, Al, Ca, and Na atoms would probably not induce re-orientation of the composition plane. Anisotropic thermal contraction would give rise to angular movements too small to be of practical significance.

Prediction of the orientation of the rhombic section.

The angle σ is a function of the cell angles and may be calculated from the relation $\cot \sigma = \cos \alpha^* / \cot \gamma$ (Story-Maskelyne, 1895) where α^* is the angle between the (010) and (001) face normals. The single crystal X-ray studies of Cole, Sörum, and Taylor (1951) and the powder X-ray investigation of Smith (1956) have provided accurate values of the lattice angles for the composition range An_0 to An_{55}. In the remaining range, only one complete set of lattice angles has been determined by X-ray methods, unfortunately for an unanalysed specimen. Study of the morphological data in the literature has led to the conclusion that most of it is of considerably lower accuracy than the X-ray data and should be disregarded. Of the six direct and reciprocal lattice angles, only α^* can be determined directly by morphological examination. The indirect procedure for determining the other angles has been so uncertain that resort has been made sometimes to the dubious procedure of calculating γ from measured values of (010):(001) and σ by the formula given at the head of this section. In spite of these difficulties, several sets of fairly accurate data have been obtained by morphological methods.

The results of the X-ray and morphological studies are displayed in fig. 1. From An_0 to An_{35}, the data are sufficient to establish the influence of the structural state and chemical composition on the orientation of the rhombic section. All but three of the natural specimens from low-temperature environments give a linear dependence betweeen σ and the An-content. The remaining three are albites that have been examined morphologically and the deviations are probably caused by errors resulting from the presence of vicinal faces. The rhombic section for the synthetic specimens is almost independent of An-content. Seven specimens illustrate the conversion by heating from the low-temperature to the high-temperature state while two specimens of andesine from volcanic environments reveal a state of partial inversion. These two specimens are of particular interest because their rhombic sections are so close to (001) that, in practice, it would be impossible to distinguish between pericline and acline-A twins.

The 'oligoclase' from Vesuvius, listed by Dana and by Hintze as the type oligoclase, is better described as a lime-bearing anorthoclase because its composition is $Or_{16}Ab_{69}An_{15}$ and the lattice angles agree with those expected for a high-temperature structure. It has been included to show that the solid solution of potash has little effect on the position of the rhombic section of high-temperature acid plagioclases. The calculations of MacKenzie (1956) for synthetic lime-free anorthoclases revealed the same independence of potash content. Data obtained by MacKenzie and Smith (1955) from experiments in which perthites of low-albite and potash felspar were heated can be used to demonstrate that the rhombic section of low-temperature acid plagioclases is also independent of the solid solution of potash felspar. From their measurements of the change of α^* and γ^* produced by the introduction of potash into the perthitic albite, and the data given by Smith (1956), it is likely that low-temperature felspars of composition Or_5Ab_{95} and $Or_5Ab_{85}An_{10}$ will have the following lattice angles respectively: α^* 86·60°, γ 87·68°; α^* 86·51°, γ 88·17°;

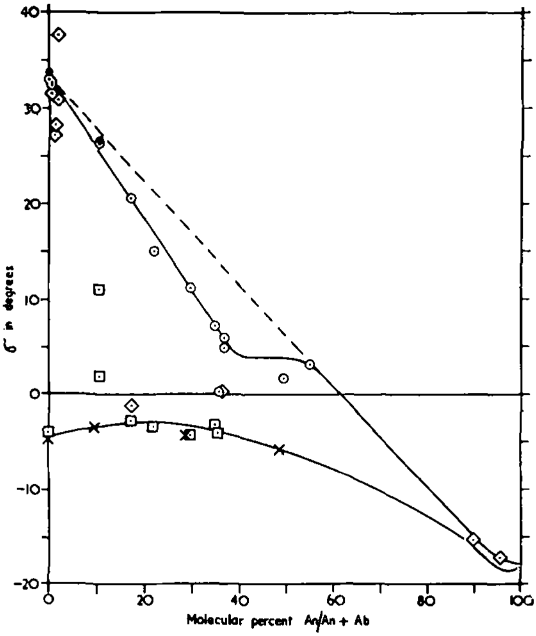

FIG. 1. The variation of σ with composition and structural state of plagioclase felspars. ○ natural, lattice angles from X-ray studies; ◇ natural, angles from morphological studies; □ heated natural; × synthetic; ● hypothetical felspars of composition Or_5Ab_{95} and $Or_5Ab_{85}An_{10}$. The upper and lower full-line curves, respectively, give the variation of σ with composition for specimens in the low and high structural states. Smith and Gay (1958) have suggested that fully ordered sodic plagioclases would fall on the broken-line curve and that the low-temperature specimens in this region are not fully ordered. The sources of the data are Cole, Sörum, and Taylor (1951), Des Cloizeaux (1862), Fels (1903), Glinka (1889), Kratzert (1921), Krebs (1921), Lewis (1914), vom Rath (1869, 1886), Smith (1956).

the positions of the rhombic section calculated from these angles hardly differ from those of corresponding natural plagioclases containing only 1 or 2 % potash felspar. As basic plagioclases carry only small amounts of potash felspar in solid-solution the effect of potash felspar on the rhombic sections of all plagioclases may be safely ignored.

The data on the lattice angles of intermediate and basic specimens are sparse; however, a recent X-ray study of the powder patterns by Smith and Gay (1958) yields supplementary information. Two good sets of morphological data on analysed basic plagioclase specimens are available: An anorthite from Vesuvius gave $\sigma = -17^\circ\ 09'$ in good agreement with the value $-16^\circ\ 45'$ obtained from the X-ray measurements of an unanalysed specimen from the same locality; although from a volcanic environment, it is probably in or near the low structural state (cf. Gay 1954). The bytownite from St. Christopher's Island is from a volcanic environment and comparison with specimens from other localities described by Gay (1954) suggests that it is probably in a transitional state.

Examination of the variation of the lattice angles with composition shows that the change in position of the rhombic section is largely caused by the variation in γ, for $\cot \sigma = \cos \alpha^*/\cot \gamma$ and $\cot \gamma$ ranges from $+0{\cdot}04$ to $-0{\cdot}02$ while $\cos \alpha^*$ ranges from $+0{\cdot}063$ to $+0{\cdot}073$. Consequently, examination of the movement of those peaks in the X-ray powder pattern that depend strongly on the lattice angle γ^* can provide information on the position of the rhombic section. Smith and Gay have recorded such information in their study of more than 100 plagioclase felspars, including all those used in fig. 1 of this paper. Examination of the figures and data show that, for the acid plagioclases, the variation in the rhombic angle σ is closely paralleled by the change in the Γ function measured by Smith and Gay. This function depends largely on γ^*, but also gives a good measure of γ, for γ varies in a proportional manner to γ^* for plagioclase felspars. Hence the orientation of the rhombic section and the Γ function would be expected to vary in a similar manner. The curves for the intermediate and basic ranges of fig. 1 have been obtained by using the few direct observations in conjunction with the observed variation in the Γ function. In spite of its indirect origin, this curve is thought to give a fairly accurate representation of the variation in the position of the rhombic section.

All the data used in the construction of fig. 1 were obtained at room temperature, so, strictly speaking, the predicted rhombic sections apply only to twin development at room temperature. Direct measurements of the variation of lattice angles with temperature have not yet been made, apart from some observations on anorthite. However, the influence of temperature—as distinct from the structural state—on twin formation may be estimated in a qualitative or semi-quantitative way. MacKenzie (1952) and Laves (1952) have shown that lime-bearing anorthoclases become monoclinic at high temperature, which means that α^* and γ probably approach 90° at the same fractional rate. As $\cot \sigma = \cos \alpha^*/$

$\cot \gamma \approx (90-\alpha^*)/(90-\gamma)$ when α^* and γ are near 90°, the rhombic section of any particular anorthoclase should be independent of temperature. This is confirmed by the agreement between the observed composition plane of pericline twins and the rhombic sections calculated from lattice angles that have been measured at room temperature (MacKenzie, 1956). Although high-temperature potassic oligoclases do not become monoclinic on heating to high temperatures, α^* and γ approach 90° as the temperature is increased (MacKenzie, 1952), and it is reasonable to suppose that α^* and γ approach 90° at the same fractional rate since there is a continuous change from potassic oligoclases to calcic anorthoclases. Thus the rhombic section of high-temperature acid plagioclases should be independent or nearly independent of temperature. Some unpublished powder X-ray measurements made by the author on low-temperature albites indicated that the change of lattice angles upon heating was moderate. As the low-temperature state is probably only formed at low temperatures it is likely that the rhombic section for low-temperature acid plagioclases is nearly independent of temperature. Mügge (1932) has shown from the lattice angles obtained by Beckenkamp that the rhombic angle of an anorthite from Vesuvius increased by 25′ as the temperature increased from 20° C. to 200° C. This suggests that the rhombic angle for low-temperature anorthite may increase by as much as 2° as the temperature of crystallization goes up to 700°–1000° C., the upper limit for the primitive anorthite type of structure (Gay, 1956). No data on high-temperature basic plagioclase specimens are available.

Therefore, for a particular structural state, it is probable that the influence of temperature on the rhombic section is small and for most practical purposes may be ignored.

Fig. 1 is suitable for the interpretation of values of σ obtained by direct measurement on the face (010), or on sections cut parallel to (010). Nowadays, however, most measurements of plagioclase twins are made optically from sections suitably orientated on a universal-stage, and the twin-elements are referred to the optical indicatrix. Figs. 2 and 3 have therefore been prepared to show the predicted orientations of the (001) plane and the pericline composition plane with respect to the principal optic symmetry axes α, β, and γ for the extreme low and high structural states respectively. The positions of the (001) pole have been taken from van der Kaaden (1951) who obtained them from consideration of observations on synthetic and natural plagioclases obtained by himself and other workers. The definition of σ as the angle between the intersections of the (001) plane and the rhombic section on the trace of (010) implies that the pole of the rhombic section may be located by using the positions of (010), [010], and (001) given by van der Kaaden and the values of σ given in fig. 1. Using this construction, figs. 2 and 3 have been prepared. Fig. 2, for specimens now in the low-temperature state, contains one curve for (001) and two curves for the predicted pericline composition plane, one each for twinning controlled by the high and low structural states. Fig. 3, for specimens now in the high-temperature state, contains three curves; if the felspar crystallizes with the high-temperature structure and no inversion occurs, curves A and B give the positions of the (001) pole and the rhombic section, respectively. As it is possible that the felspar once had the low-temperature structure and has

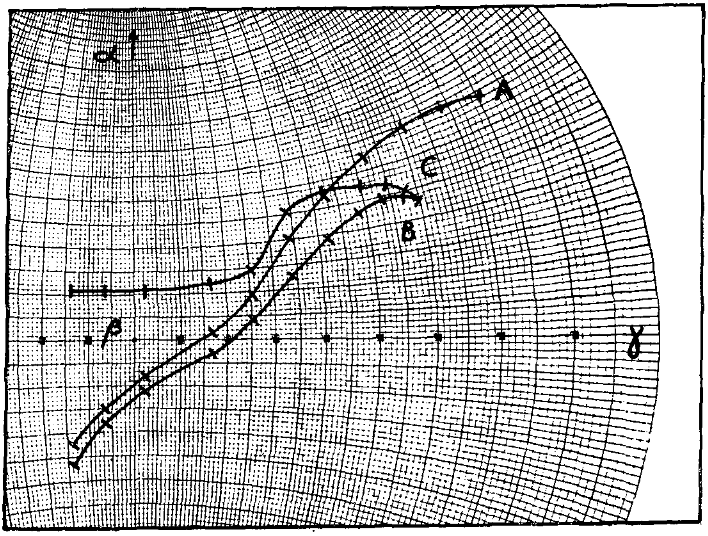

FIG. 2.

FIGS. 2 and 3. The orientation of the pericline composition plane, the rhombic section, and the (001) pole relative to the optical indicatrix of plagioclase felspars. A, the (001) pole; B and C, pericline composition planes, B for twinning established while the felspar was in the high structural state and C for twinning established while it was in the low structural state, and assuming in either case that any subsequent inversion has not affected the composition plane. Fig. 2 (*above*) is for felspars now in the low structural state and the rhombic section is given by curve C. Fig. 3 (*opposite*) is for felspars now in the high structural state and the rhombic section is given by curve B. The cross-marks indicate the compositions An_0, An_{10}, ⋯ An_{100} running from left to right. Based on van der Kaaden (1951) and fig. 1.

inverted as a result of high-grade metamorphism, curve *C* is given to show the predicted position of the composition plane for twinning occurring before inversion. Fig. 4 shows the regions that may be occupied by the (001) pole and the pericline composition plane for all possible compositions and structural states.

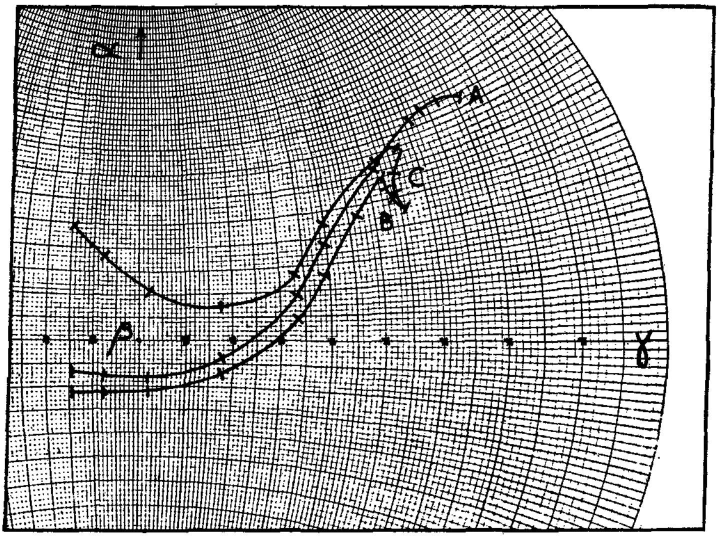

FIG. 3.

Interpretation of the observations.

The goniometric and universal-stage measurements of the composition planes of *b*-axis twins are displayed in figs. 5, 6, and 7. High accuracy cannot be expected for all the measurements because the composition plane of pericline twins is often irregular (e.g. Gysin, 1925), while the occasional use for reference of positions of (001) taken from standard optical migration curves may lead to further uncertainty. The universal-stage measurements are plotted in two groups: those in fig. 6 arise from plagioclases whose environment indicates a low structural state, while those in fig. 7 come from volcanic or hypabyssal specimens of uncertain structural state. In fig. 6 it is necessary to plot only three reference curves: (001), the rhombic section for the low structural state, and the relict rhombic section for the high structural state. In fig. 7 it is necessary to show two additional curves to cover the possibility of plagioclases

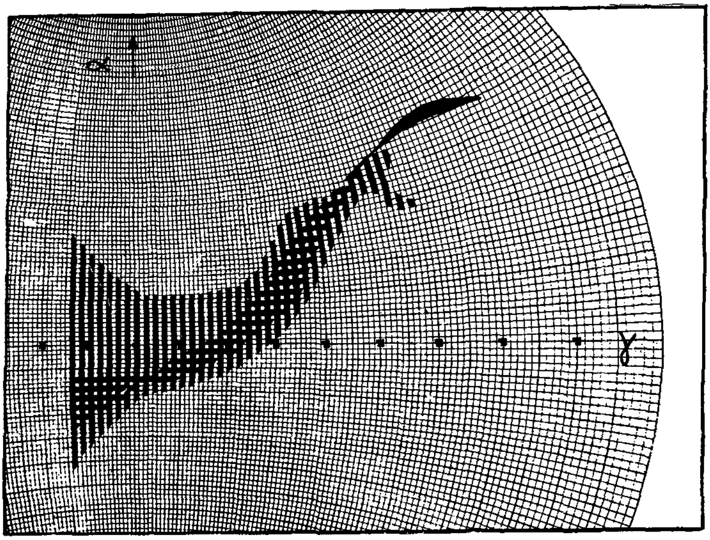

FIG. 4. The possible positions of the (001) pole and of the pericline composition plane with respect to the optic symmetry axes α, β, and γ for all compositions and structural states. The horizontal shading represents the (001) pole and the vertical shading the pericline composition plane.

not in the low state; the two extra curves show the regression of (001) and the rhombic section for the high state (the possibility of high-grade metamorphism of an original low plagioclase is ignored, thus permitting the omission of the relict rhombic section for the low structural state).

If all the plagioclases had reached equilibrium, and if acline-A and pericline twins adopted the theoretical composition planes, the composition planes of *b*-axis twins would be parallel to either (001) or the rhombic section of the low structural state. The observed data fall only partly on these two theoretical planes and the deviations might be caused by one or more of the following: experimental error, structural inversion or change of chemical composition, initial adoption of a composition plane other than (001) or the rhombic section. Examination of the figures shows that a few values for albite specimens and many values for bytownites and anorthites are not consistent with either (001) or the rhombic sections. The deviations for albite cannot be explained as the result of either compositional or structural changes, and it seems likely that they result merely from experimental error in the measurement of σ

or in the location of the reference curves for (001) and the rhombic section. The discrepancies for the basic specimens (fig. 5) are more prominent, but the deviations are probably more apparent than real, for

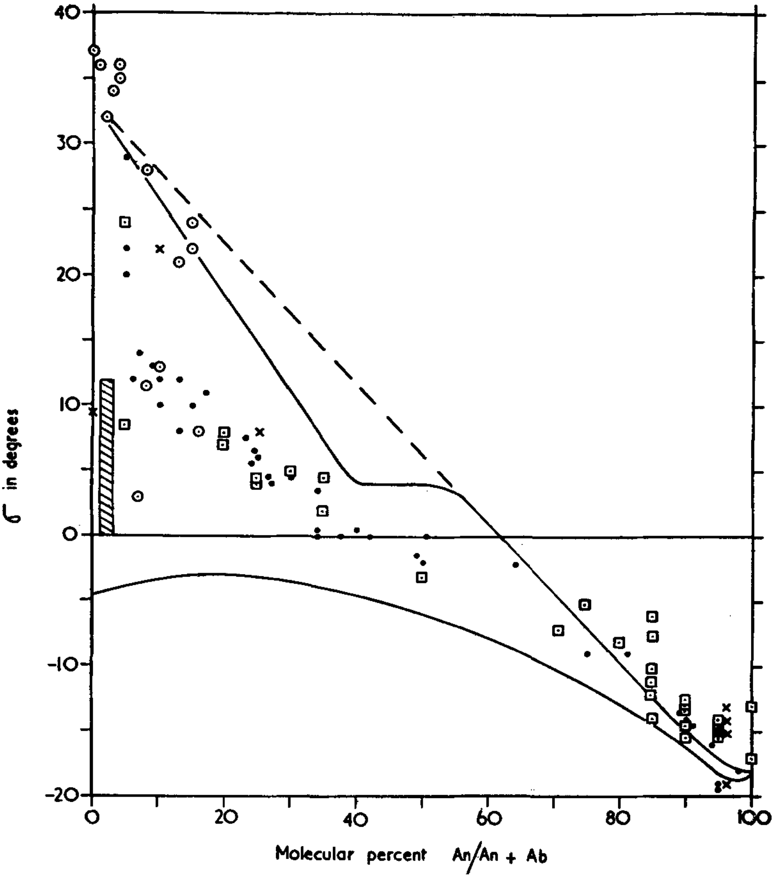

Fig. 5. Comparison of observed σ values with the theoretical curves. ○ Barth (1928); ● Schmidt (1915); □ Barber (1936); ×, in order of An-content, Penta (1933), Glinka (1894), Crawford (1926), and Mügge (1930). The shaded area covers the range of values obtained for albites from Alpine schists by Lewis (1914) and by Smith.

most of the chemical compositions were estimated optically and listed only to the nearest 5 % An (Barber, 1936). In addition the theoretical variation of σ for these compositions is uncertain. Thus the conclusion reached by vom Rath in 1876, that the pericline twin adopts the rhombic section for its composition plane, is confirmed, though not as conclusively as might be desired.

Examination of the figures shows, in agreement with Gysin (1925), that a clear distinction can be made between acline-A and pericline twins for specimens more basic than An_{70}. Over the range An_0 to An_{60}, many of the specimens cannot be assigned with certainty to either twin law as the observed composition planes do not differ from (001) by more than the possible experimental error. The others may be unambiguously assigned to the pericline type and the observed value of σ in relation to the theoretical curves may be used to obtain some information about the state of the felspar at the time twinning occurred.

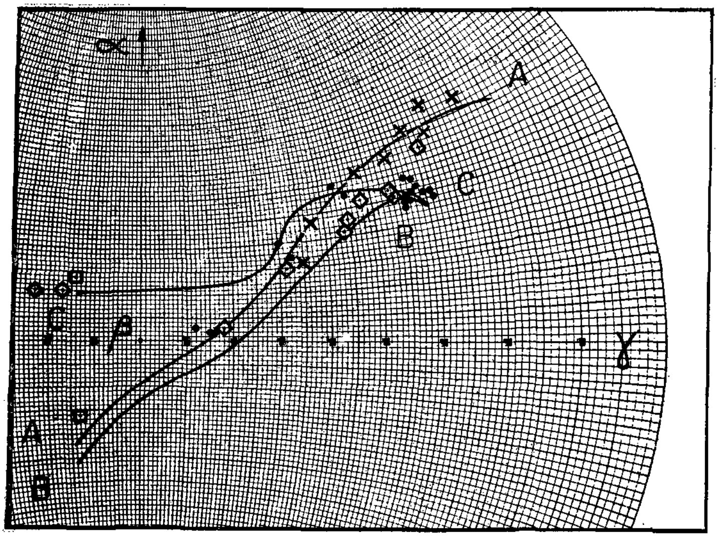

Fig. 6. Comparison with the theoretical curves for pericline and acline-A twins of the observed composition planes for plagioclases that are probably in the low structural state. □ Phillips (1929); ◇ Dolar-Mantuani (1952, the two sodic specimens), Hermann (1924, the eight more calcic specimens); ● Gysin (1925); × Bradley (1953). The points should lie on curve *A* for acline-A twins, on curve *C* if twinning was established with the felspar in its present state, and on curve *B* if twinning was established while the felspar was in a high structural state and the composition plane was not affected by subsequent inversion.

The albites and oligoclases from microcline perthites, with one exception, give values that lie on or close to the theoretical rhombic section for the low structural state. This is to be expected whether the albite forms by exsolution or replacement. The exception has $\sigma = 3°$ and could either be an acline-A twin with a 3° error of observation (as suggested by Phillips, 1929) or a pericline twin controlled by a structural state close to the extreme high state; the latter would not be surprising, for MacKenzie and Smith (1955, and unpublished) have found that some rare microcline perthites contain an anorthoclase, which has a rhombic section similar to that of high albite.

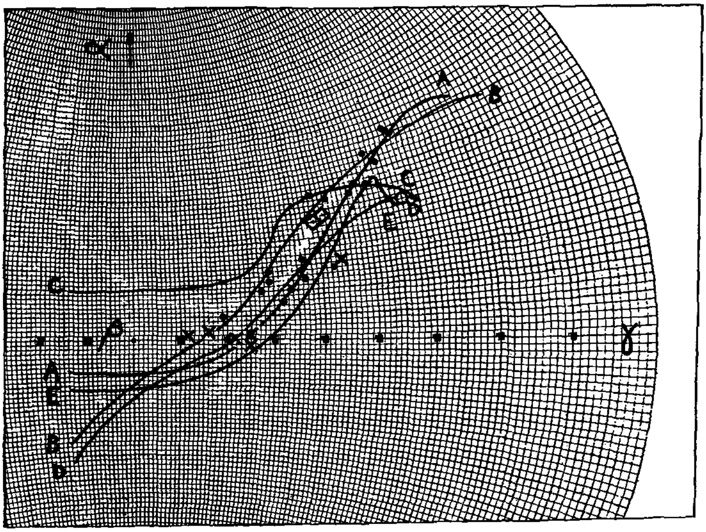

Fig. 7. Comparison with the theoretical curves for pericline and acline-A twins of the observed composition planes for plagioclases that may be either in or between the high and low structural states. × Bradley (1953); ● Gysin (1925); ◇ Campbell Smith (1928); ○ Lundegårdh (1941). Curves *A* and *B* give the position of the (001) pole for the high and low structural states, respectively. Curves *C* and *E* are the rhombic sections for plagioclase felspars in the low and high structural state, respectively. Curve *D* gives the pericline composition plane for a felspar in which the pericline twinning was established while the felspar was in the high structural state and in which subsequent inversion to the low structural state did not affect the composition plane.

The possibility of compositional changes complicates the interpretation of the observed twin relations, for a change of composition unaccompanied by a corresponding movement in the composition plane results in a composition plane consistent with a different structural state. Fortunately, compositional changes in the plagioclases of igneous rocks are probably rare, as the persistence of fine-scale zoning indicates. In veins, and possibly in metamorphic rocks if recrystallization does not occur, compositional changes subsequent to the establishment of the twin boundary may be important. Thus Professor F. Laves and Dr. T. Schneider of Zürich have recently[1] provided evidence for compositional changes in the variety of albite known as pericline that occurs in cavities in Alpine chlorite–albite schists. They found that the σ angles in the pericline twins are commonly 9°–10°, that the crystals are milky in appearance, containing holes and enclosures, that the extinction is irregular, and that the pericline often has a clear shell of albite. Measurements by Lewis (1914) and by the present author are in accord with those of Laves and Schneider. Lewis described a pericline triplet with a σ angle ranging from 7·5° to 11°, while the present author has found various values for specimens in the Cambridge museum ranging from 0° to 20° with averages taken over a single specimen ranging from 0° to 12°. X-ray powder measurements have invariably indicated a low structural state with a composition close to pure albite. Laves and Schneider concluded that it was likely that pericline crystals were once oligoclase but have suffered a change of composition that has led to their irregularity of texture and extinction. The alternative, that the pericline grew as albite in a high or intermediate structural state, is regarded as unlikely. The present author agrees with this view but nevertheless believes that some of the intermediate σ angles of other albites and oligoclases (see fig. 5) definitely indicate twinning while the plagioclase was in a high or intermediate structural state, since the original descriptions give compositions ranging all the way from An_0 to An_{30} and many of the specimens do not have the characteristics of the Swiss pericline.

So long as compositional changes can be ruled out, the possibility exists of demonstrating changes of structural state in pericline-twinned plagioclase. The present structural state can readily be estimated by X-ray, infra-red, and optical methods, while the pericline composition plane provides evidence of an earlier structural state. Examination of figs. 5, 6, and 7 shows that the effect of structural state on the composition plane falls off rapidly with the An-content and that estimation of the original structural state is, in practice, confined to plagioclase in the albite–oligoclase range, though in favourable cases some indication might be obtained for andesine and labradorite.

In conclusion, it should be emphasized that many qualitative and semi-quantitative arguments have been used in this paper, which may not

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[1] Preliminary summary in Schweiz. Min. Petr. Mitt., 1956, vol. 36, p. 622.

stand the test of further experimental investigation. Accurate measurements of the cell dimensions of basic plagioclases, both at ordinary and elevated temperatures, together with measurements of sodic plagioclases at elevated temperatures, are needed both for the present and other purposes. A systematic study of pericline-twinned plagioclases, obtained from known petrological environments, is needed to provide a more rigorous test of the predicted orientation than the one given in this paper. The author hopes that the present account will provide the stimulus for such investigations.

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