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THE RECOGNITION OF PLAGIOCLASE TWINS IN SECTIONS NORMAL TO THE COMPOSITION PLANE

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ABSTRACT

In sections of plagioclase twins cut normal to the composition plane, the law of twinning can often be recognized without the aid of the universal stage by considering the birefringences and extinction angles of the twin individuals. Three diagrams, one for each of the important composition planes, facilitate this recognition. When the twinning is lamellar, the distinction between the albite and acline-pericline laws is always easily accomplished.

INTRODUCTION

In the beginning of this century the development of the universal stage gave the opportunity of studying in great detail the optical properties of the members of the plagioclase group. In the period from 1914 to 1924 their optical orientation and their various laws of twinning were studied exhaustively (Fedorov and Nikitin, Wülfing, Duparc and Reinhard, Berek and others). Yet, in most cases the types of twinning were not studied for their own sake: they served, in conjunction with the optical orientation, to determine the chemical composition (*i.e.* the percentage of anorthite) of the plagioclase.

Several other methods to determine the composition are practicable without the universal stage. They make use of characteristic extinction angles in specific sections or zones (Michel-Lévy, Schuster, Fouqué, Köhler and others). These methods are now used far more universally than those designed for the universal stage. Their application does not require much knowledge of the basic facts and concepts underlying them. Yet lack of insight may lead to wrong results. Even the directions for the use of these methods, as given in many textbooks, often contain inaccuracies.

In the last decade a growing interest can be noted in the mode of occurrence and the distribution of the various laws of plagioclase twinning in different rocks. Gorai (1951) distinguishes between two groups, "A-twins" (usually lamellar) and "C-twins" (non-lamellar or composite).* His study of the frequency of A- and C-twins in many rocks shows interesting differences between plagioclase of magmatic and of metamorphic origin. Attractive in his method is the possibility to distinguish between both groups without the aid of the universal stage. Yet a more detailed classification would have advantages. For instance, in

* The criteria given by Gorai to distinguish between simple A-twins and C-twins are only correct for twins with (010) as composition plane.

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 (Turner 1951, Tobi 1959). Again, in albite porphyroblasts of certain low-grade metamorphic schists the Carlsbad and albite laws are both found, whereas twins with composition planes other than (010) are rigorously absent (Tobi 1959). As a final example it may be mentioned that rocks such as spilites and trondhjemites occasionally show a large number of Ala-A twins, combined with albite lamellae. Under favorable circumstances these patterns may serve to distinguish between otherwise similar rocks, or to indicate the origin of clastic grains in an arenite. Eventually, a more extensive research into the occurrence of the various twin laws in different rocks might shed some light upon the conditions favoring their development, which would be of great petrological importance. *The present article has been written with the double purpose of stressing some basic facts underlying current determination methods, and of facilitating the recognition of the various laws of twinning without the aid of the universal stage.*

The Properties to Be Studied

When studying a plagioclase twin without a universal stage our information consists chiefly of the *extinction angles* and the *birefringences* found in both individuals of the twin. Nieuwenkamp (1948) constructed charts for the determination of the An-content from these properties in random sections of albite twins. In the present paper our chief aim will be to determine not the An-content, but the law of twinning. *To this end we will use only sections of twins cut perpendicular to their composition plane.*

This following portion deals with the question of how such sections are found and how the necessary information is obtained from them. To make an intelligent use of this information, it should be realized that the optical properties of the individuals of a twin are chiefly conditioned by:

1) the optical orientation of the particular plagioclase.
2) the law of twinning.
3) the orientation of the section.

Selecting sections normal to the composition plane

A plagioclase twin is usually visible with crossed nicols only. This visibility may be caused by a difference in extinction angle, in birefringence, or in both. The plane of contact between the twin individuals is called the composition plane. In sections normal to this plane, to which the present method is confined, the trace of this plane should be a sharp line. It should not move laterally when the focus of the objective with the highest magnification is lowered from the upper to the lower surface of the thin section.

When the composition plane is irregular or in other ways does not agree with the "ideal" composition plane, the method is not practicable.

Distinguishing between symmetrical and asymmetrical extinctions

When the extinctions are symmetrical with regard to the trace of the composition plane, the twin individuals show equal illumination in each 0° and 45° position of this trace. This means that the twin becomes almost invisible in those positions. When the extinctions are asymmetrical, one would expect the twin to be visible in both the 0° and 45° positions. In reality, the difference in intensity of the transmitted light is often visible in one of these positions only, *viz.* in that nearest to the extinction positions.

Determining the elongation with regard to the composition plane

It suffices to insert the gypsum plate while *the trace of the composition plane* is in the NE 45° position. With most microscopes the twin individuals will become yellow when the elongation is negative (length fast), blue when it is positive (length slow). In the following this is assumed to be the case. It should be noted that the term elongation is used here in a not too literal way, as the form of the crystals is of no importance. It should be borne in mind too that the extinction angles given in the literature always refer to X′ (the vibration direction of the ray with the smaller refractive index). Thus, when the elongation is positive the extinction angle must be over 45°. The sign of the elongation should not be confused with the sign of the extinction angle.

Determining the sign of the extinction angle

Some special attention should be given to the confusing matter of the extinction sign. According to common usage, *extinction angles measured from a cleavage or composition plane in a clockwise direction are considered positive, those measured in counter clockwise direction negative.* This extinction sign has only relative importance, because it is reversed by turning the section upside down. To avoid ambiguity in the reading of tables and diagrams, it became customary to give the extinction angle $X' \wedge (010)$ on (001) as seen from the *positive* side of the *c*- axis, the angle $X' \wedge (001)$ in sections on (010) as seen from the *positive* side of the *b*-axis, and the angles $X' \wedge (010)$ and $X' \wedge (001)$ in sections normal to *a* as seen from the *negative* side of the *a*-axis (cf. Duparc and Reinhard, 1924, p. 22). Unfortunately, it is seldom possible to ascertain the crystallographic orientation of plagioclase crystals in a thin section. An exception must be made for the section normal to *a*, to which will be devoted a separate paragraph (page 1480).

In this paper, the extinction sign will be chiefly used in a relative way to compare the extinction angles of the two individuals of a twin: if both angles are measured from the trace of the composition plane in the same direction the signs agree, if they are measured in opposite directions the signs are opposite.

The extinction positions are easily determined on rotating the stage. When the extinction angles are large, or when composite twins are studied, it may prove useful to insert the gypsum plate while the trace of the compsition plane is in the 0° position. Twin individuals with positive extinction will then become yellow, those with negative extinction blue. Thus, in this position twin individuals with symmetrical extinctions will always show different colors.

Estimating the birefringence

For the present purpose a rough estimation of the birefringences found in twins cut normal to the composition plane will usually be sufficient. In the diagrams four groups are distinguished, limited by the following values:

0.002: almost optically isotropic
0.004: birefringence like that of apatite
0.008: birefringence near that of quartz.

The Optical Orientation of Plagioclase

In the plagioclase group a distinction can be made between a *high-temperature* and a *low-temperature form*, the former being virtually restricted to volcanic rocks. The optical properties are slightly different, but for the problems under consideration these differences do not seem to be of great importance. The diagrams given here refer to low-temperature optics.

The *optical orientation of plagioclase* may be studied in a stereographic projection on a plane normal to the crystallographic *a*-axis (Wulff net, Fig. 1)*. In this projection the important cleavage- and composition

* The original diagram given by Duparc and Reinhard (1924) was oriented on the negative side of the *a*-axis, as the conventional extinction signs are based on this orientation. The present author has chosen the orientation on the positive side of the *a*-axis to facilitate comparison with crystal drawings, which are always drawn with the positive *a*-axis pointing to the observer and the positive *c*-axis pointing upward. Winchell and Winchell (1951) use the same orientation in their Fig. 172, but here the optical orientation is not correct.

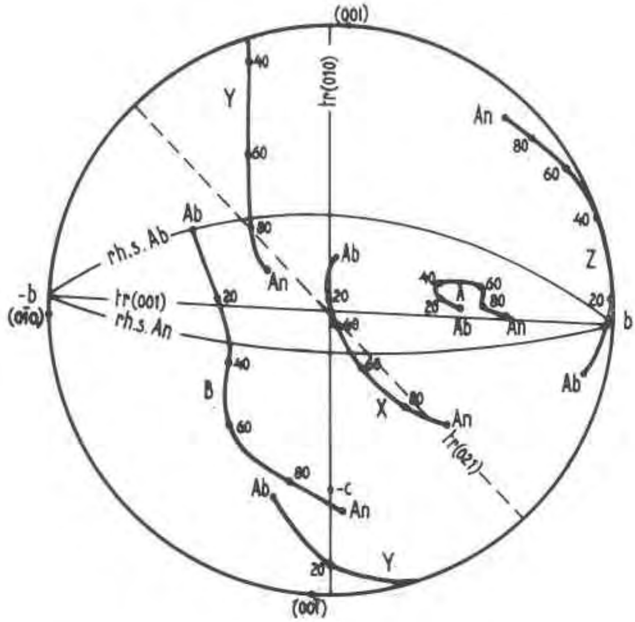

FIG. 1. Optical orientation of the low-temperature plagioclases, shown in stereographic projection on a plane normal to the *a* axis. The cleavage- or composition-planes (010), (001) and (021) appear as straight lines. The rhombic sections (rh.s.) of the end members albite (Ab) and anorthite (An) are indicated by great circles. The left Baveno composition plane (0$\bar{2}$1) is not indicated. (Modified after Duparc and Reinhard)

planes (010) and (001), making an angle of 94° with each other, appear as diameters of the net. Therefore, the properties of sections cut normal to these planes are read conveniently from this diagram. The composition trace of one of the Baveno laws appears as a dashed line (tr. (021)). The composition plane of the pericline law is obtained by tilting from the (001) plane around the *b*-axis over an angle dependent on the An-content (Fig. 2). The position of this plane (the "rhombic section") for the end members of the plagioclase group (albite and anorthite) is indicated by great circles in Fig. 1.

The change of orientation of the indicatrix with increasing An-content can be roughly described as a rotation around the optic axis A. The change in the positions of the optic axes A and B is also controlled to some extent by differences in optic axial angle.

Let us now consider how the optical properties of sections normal to the various composition planes are controlled by this optical orientation, so that we may distinguish between those planes in favorable cases.

Sections normal to (010)

In plagioclase with less than 75% An, Z is the indicatrix axis nearest to the normal on (010) (Fig. 1). Hence, this plagioclase must show *negative elongation with regard to (010)*. The closer Z is to the normal on (010), the smaller is the extinction angle. Generally the optic axes A and B are distinctly oblique to (010). Only when the An-content surpasses 75% the axis B lies in or nearly in (010). This implies that sections normal to (010) always show appreciable birefringence when the An-content is below 75%.

The actual properties as shown in Fig. 3 confirm these statements. In this diagram the birefringences and extinction angles are drawn as "contours." The chemical composition is plotted along the abscissa, the orientation of the normal on the section in the zone normal to (010) along the ordinate. *Thus, the line marked c indicates the section cut perpendicular to the c-axis.* Each imaginary vertical line in the diagram indicates the extinction angles and birefringences found when a plagioclase of definite composition is turned in the zone normal to (010). The maximum extinction angle to occur in this plagioclase is indicated by the extinction curve tangent to this vertical line. The dominance of negative elongation (angles smaller than 45°) and appreciable birefringence in the

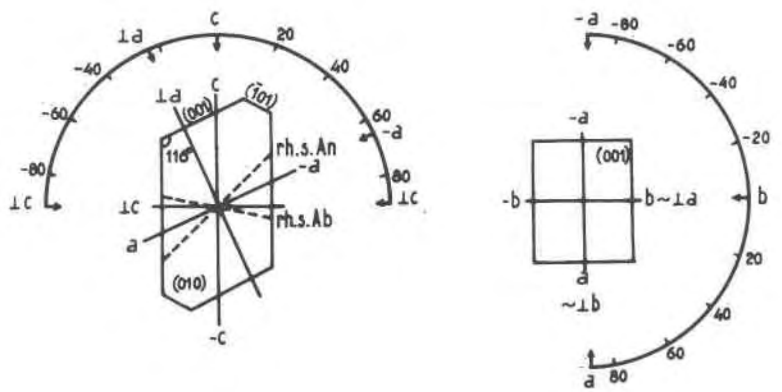

FIG. 2. (Left) Section parallel to (010), with indication of the crystal- and twin-axes lying in this plane, and of the traces of the rhombic section (rh.s.) for albite and anorthite. The arc shows that part of the zone perpendicular to (010) covered by Fig. 3, with indication of the angles used to fix the orientation.

FIG. 2. (Right) Section parallel to (001), with indication of the crystal- and twin-axes lying in this plane. The *a*- and *b*-axes are nearly at right angles, so that the normal of one of them in the plane (001) is optically indistinguishable from the other. The arc shows that part of the zone perpendicular to (001) covered by Fig. 4, with indication of the angles used to fix the orientation.

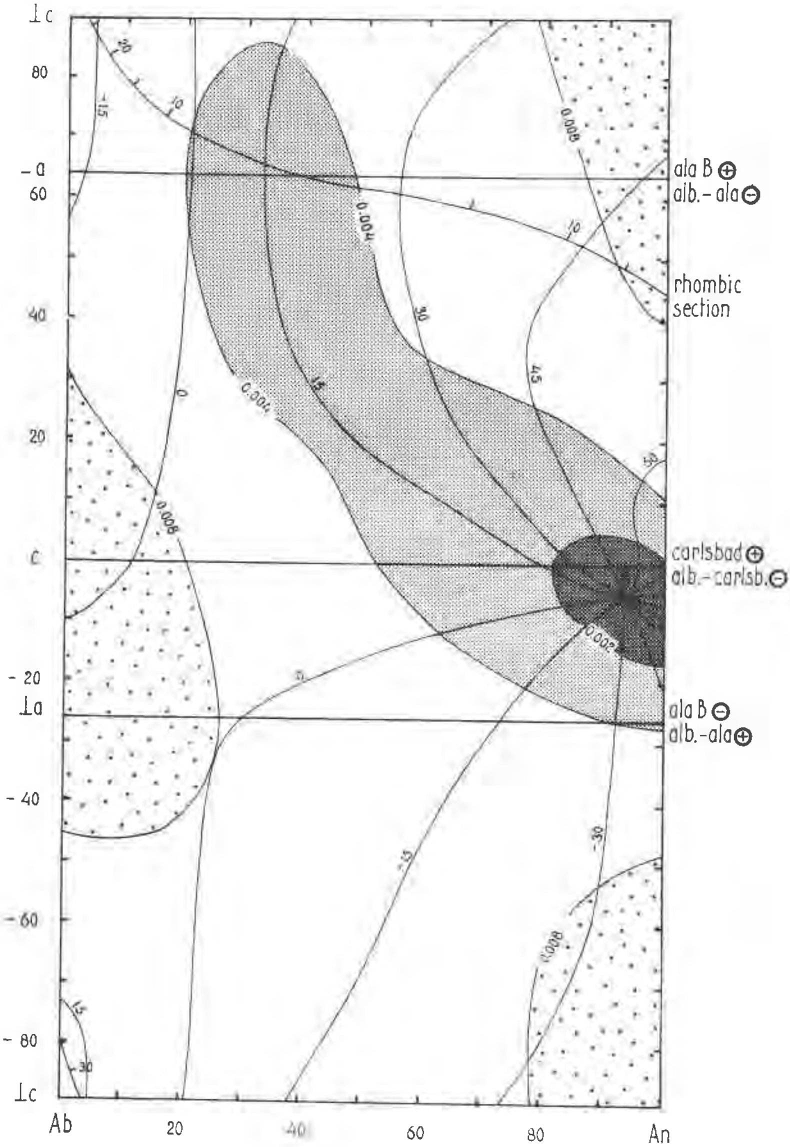

FIG. 3. Extinction angles $\chi' \wedge 010$ and birefringences in the zone normal to (010). *The optical properties refer to sections normal to the directions indicated along the ordinate.* The individuals of a *normal twin, i.e.* an albite twin, occupy one and the same point in the diagram, the extinction of the second individual being found by reversal of sign. The individuals of a *parallel or complex twin* are represented by two points situated symmetrically with regard to the horizontal line bearing the name of that twin law in the margin of the diagram. These points indicate the optical properties of the twin individuals, when the

zone normal to (010) stands out clearly in the diagram.

It should be borne in mind that the chart shows only half of the zone normal to (010). The other half is identical but for the extinction signs, which are opposite. This fact need not worry us, because the extinction signs will be used here in a relative way only. For cases where the conventional extinction signs of specific sections are needed, that part of the zone covered by the diagram is indicated by an arc in Fig. 2 (left).

Sections normal to (001)

In Na-rich and intermediate plagioclase, Y is nearest to the normal on (001). Hence, *the elongation of this plagioclase with regard to (001) may be positive or negative* depending on the orientation of the section. The optic axis A always makes a small angle with (001).When the An-content is between 10% and 35%, the same holds true for the axis B. This means that *in the zone normal to (001) all plagioclases may show sections remaining dark on turning the stage.* The neighborhood of the optic axes results also in widely varying extinction angles.

These tendencies appear clearly from Fig. 4, which gives the extinction angles and birefringences in the zone normal to (001). The fields representing sections with nearly isotropic character or very weak birefringence cover a large part of the diagram. Large extinction angles are frequently encountered. The orientation in this zone is given with regard to the *b*-axis. As the *a*-axis is very nearly normal to the *b*-axis (with small variations depending on the An-content), the section parallel to *b* may be considered identical with that normal to *a*. For cases where the conventional extinction signs of specific sections are needed, that part of the zone covered by the diagram is indicated by an arc on Fig. 2 (right).

Sections normal to the rhombic section

The position of the rhombic section differs appreciably from (001) for compositions near the end members of the plagioclase group. For compositions of ca 20–8C% An the angle between both planes is less than 10°; at about 40% An both planes coincide (Figs. 1, 2, 3). The resulting differences in extinction angles and birefringences appear clearly

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name of the twin law is provided with a ⊕ sign. The ⊖ sign denotes that the sign of one of the extinction angles as found in the diagram should be reversed to obtain the optical properties for that twin law.

Along the line representing the rhombic section, the angle with (001) is indicated in degrees. That part of the zone covered by the diagram is indicated by an arc in Fig. 2 (left). For further explanation see text.

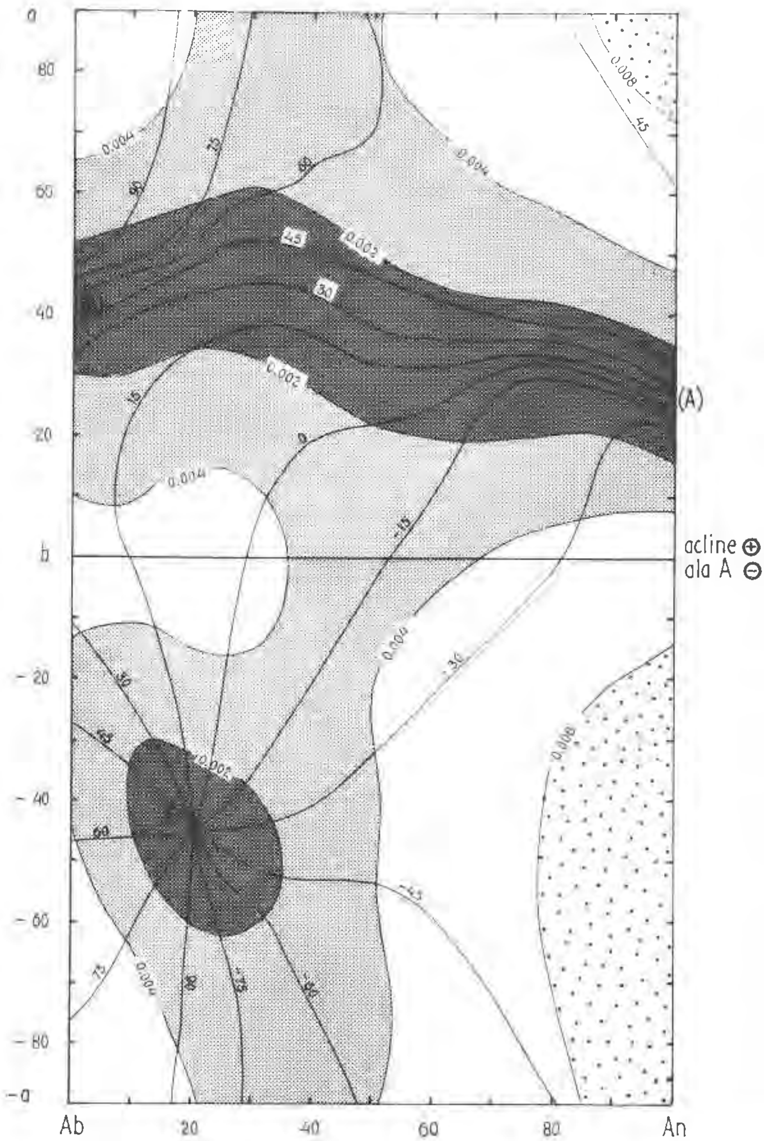

FIG. 4. Extinction angles $\chi' \wedge 001$ and birefringences in the zone normal to 001. That part of the zone covered by the diagram is indicated by an arc in Fig. 2 (right). For explanation see Fig. 3.

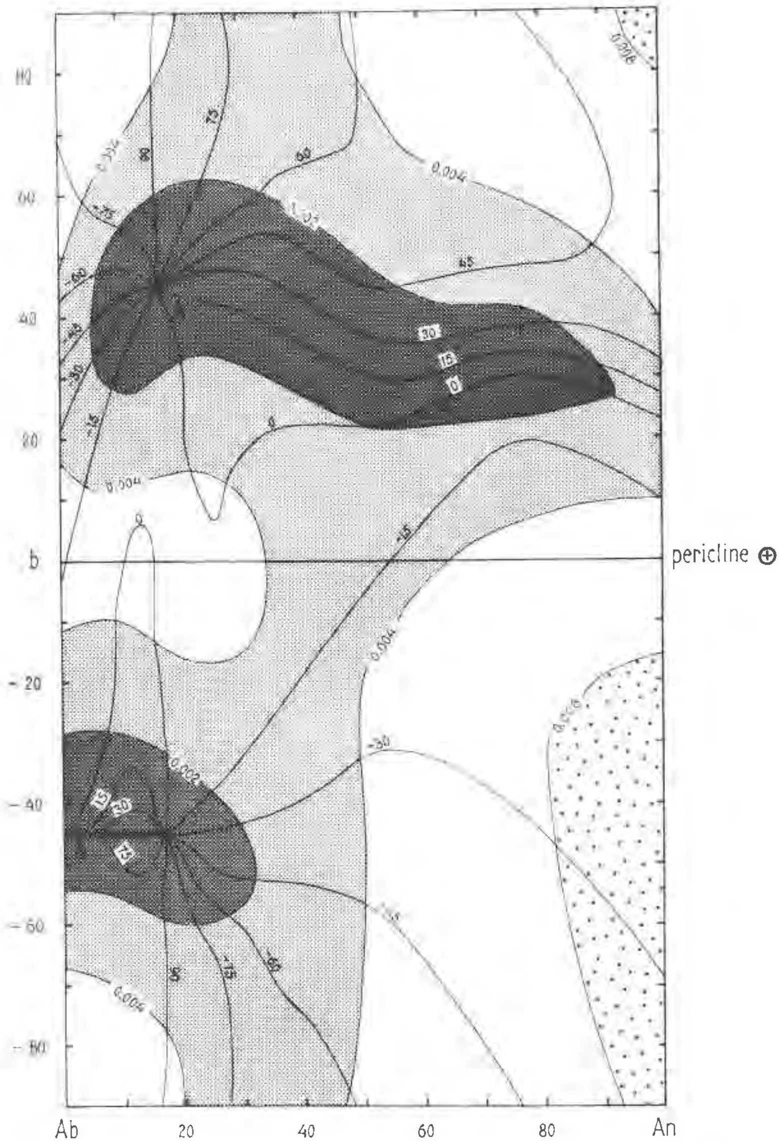

FIG. 5. Extinction angles $\chi' \wedge$rh.s. and birefringences in the zone normal to the rhombic section. For explanation see Fig. 3 and text.

by comparison of Figs. 4 and 5. These differences are best explained by considering the position of the optic axes A and B with regard to both planes. Thus, for pure albite the axis B lies just in the rhombic section, while the axis A makes a considerably larger angle with that plane than with (001). At a composition near 20% An the axis B lies again in the rhombic section, while in the interval between 0 and 20% the angle remains very small. In Fig. 5 this interval is represented by a heavy black line. Again, the larger angles with the axis A for the end members result in the 0.002 contour closing around A in the upper part of the diagram.

Sections normal to (021) or (0$\bar{2}$1)

These composition planes may be recognized by their making angles of roughly 45° with the cleavage directions (010) and (001). Even if no cleavage is visible, their nature is often betrayed by their oblique position with regard to the crystal outlines. No attempt is made here to distinguish between the zones normal to (021) and (0$\bar{2}$1). Therefore, no diagrams are given for these zones. Some general rules may be read from Fig. 1 in the same way as was done for the other composition planes. The trace of (0$\bar{2}$1) is not indicated; it should be approximately normal to the dashed trace of (021).

Section normal to a

In this section both cleavage- or composition planes (010) and (001) are visible as sharp traces enclosing an angle of 94°. The optical properties of this section for the various members of the plagioclase group may be read along the line marked -*a* in Fig. 3. When the An-content is between 0% and 75%, the elongation is always negative with regard to (010),

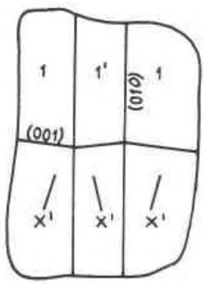

FIG. 6. Section normal to *a* of an albite twin of albitic composition. The conventional negative extinction sign for this section, as given in tables and charts, refers to the individual 1′, which is seen from the negative side of the *a*-axis.

positive with regard to (001). Thus, the elongation is now alone sufficient to distinguish between both traces.*

To obtain the conventional extinction sign, this section should be regarded from the negative side of the *a*-axis. If the (010) trace is oriented in the N-S position, the (001) trace dips to the right when the section is observed from the positive, to the left when it is observed from the negative side of the *a*-axis. In the albite twin of albitic composition shown in Fig. 6, the conventional negative extinction sign refers to the individual 1′, in which the negative *a*-axis points to the observer. The extinction angle of this individual complies with two rules:

1) X′ points to the obtuse angle between (010) and (001);
2) X′ is measured anticlockwise from (010).

When we now consider the individual 1, the attachment of an extinction sign is a matter of free choice. If we need the conventional extinction angle to determine the An-content, we choose the first rule: both individuals now have the negative sign demanded for albite in current tables and charts. The rule is valid for this particular section only. In the present paper the second rule is chosen: for our method the individuals of an albite twin should always have opposite extinction signs, as their extinction angles are measured from the (010) trace in opposite directions.

If the trace with positive elongation is not a cleavage, but a composition plane of lamellar twinning, the section might be normal to the rhombic section instead of normal to (001). The ensuing differences in extinction angle and birefringence, which may be read from Fig. 3, are only important for Ca-rich plagioclase.

The Laws of Twinning

In Table I the various laws of twinning are arranged according to composition plane and type of twinning. In the preceding section we have studied the extinction angles and birefringences occurring in sections normal to these composition planes. The Carlsbad B twin is not here considered, since it is extremely rare. We will now see how the position of the twinning axis determines the particular combination of optical properties found in the twin individuals. Before starting our enquiry into the various types of twinning, we should remember that the plagioclase crystal has a center of symmetry. Therefore, each twin must have a symmetry plane, situated perpendicular to the twinning axis.

* Above 75% An, the large extinction angles make a distinction more difficult.

TABLE I. LAWS OF PLAGIOCLASE TWINNING

Composition plane	Normal twinning	Parallel twinning		Complex twinning	
		Axis	Law	Axis	Law
(010) = cleavage	**albite** (often lamellar)	*c*	**Carlsbad A**	⊥*c* in (010)	**albite-Carlsbad**
		a	*Ala B*	⊥*a* in (010)	albite-Ala
(001) = cleavage	Manebach	*b*	**acline** (often lamellar)	⊥*b* in (001)	=Ala A
		a	Ala A	⊥*a* in (001)	=**acline**
∥b∼(001) rhombic section		*b*	**pericline** (often lamellar)		
∥*c*∼(100)		*c*	*Carlsbad B*		
(021), (0$\bar{2}$1)	Baveno				

Laws in **bold face**: very common.
Laws in *italics:* rare.

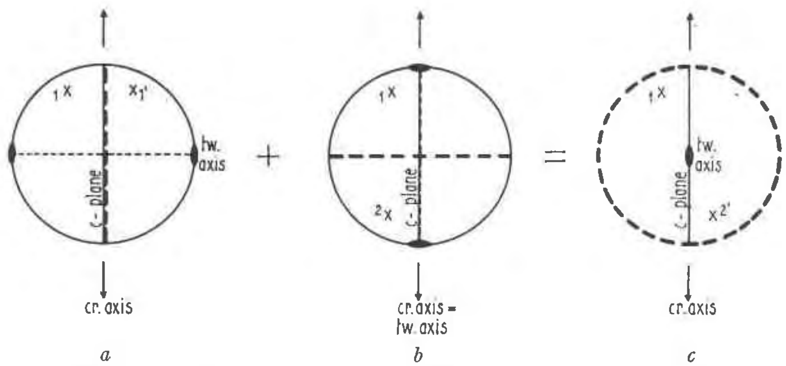

FIG. 7. Stereograms indicating the positions of the twin axis and symmetry plane (heavy dashes) with respect to the composition plane for the three types of plagioclase twinning. (*a*) Normal twinning, (*b*) parallel twinning and (*c*) complex twinning. c-plane = composition plane; tw. axis = twinning axis; cr. axis = crystal axis. One of the crystal axes is horizontal and lies in the composition plane. The effect of the symmetry operation is shown for one particular direction (1) in one of the individuals. It will be seen that complex twinning is equivalent to an addition of the symmetry operations of normal and parallel twinning.

Normal twinning

The twin axis of the normal twin is situated normal to the composition plane. Accordingly, the symmetry plane of the twin coincides with this composition plane (Fig. 7*a*). Therefore, in sections normal to this plane the individuals of such twins show the same birefringence, while the extinction angles are equal and of opposite sign, *i.e.*, the extinctions are symmetrical with regard to the trace of the composition plane.

In Figs. 3 and 4 the optical properties of both individuals of a normal twin are represented by one point only, the extinction angle of the second individual being found by reversal of sign. The composition plane of the normal twin should be a rational lattice plane: irrational planes such as the rhombic section are not found here.

Parallel and complex twinning. Basic concepts

The twin axis of a parallel twin is a crystallographic axis lying in the composition plane (Fig. 7*b*). The twin axis of a complex twin is also situated in this composition plane, but at right angles to a crystallographic axis (Fig. 7*c*). Perhaps the name complex twin is unfortunate: it should refer only to the position of the twinning axis, not to a possible complex appearance of the twin. A complex twin may well consist of two single individuals. The complex twin may also be thought of as having resulted from the successive operation of a normal law and a parallel law with the same composition plane (*cf.* the positions of 1, 1′ and 2′ in Fig. 7). When a twin shows several individuals with parallel composition planes, but with three or more different extinction positions or birefringences, more than one type of twinning must be present.

In the plane (010) the *a*- and *c*-axes enclose an angle of 116°. Thus, the complex twin axes $\perp a$ and $\perp c$, differing markedly in direction from the crystallographic axes, give rise to the complex albite-Carlsbad and albite-Ala twins (Fig. 2, left). On the other hand, in the plane (001) the *a*- and *b*-axes are very nearly perpendicular to each other (Fig. 2, right). Therefore, the complex twin belonging to one of these axes is optically indistinguishable from the parallel twin of the other.

Since an immediate distinction between parallel and complex twin laws is usually impossible, these laws will be treated together.

Parallel and complex twinning. Optical characteristics

In both twin types the twin axis lies in the composition plane, so that the symmetry plane must be at right angles to this plane. Thus, sections normal to the composition plane may make any angle with the symmetry plane of the twin. Theoretically, the twin individuals in these sections should generally have asymmetrical extinctions and different birefringences. This may be illustrated by considering the change in position of the directions 1 and 2 on turning the section of Fig. 7*b* about the normal of the composition plane. Two sections in this zone need our special attention:

(1) The section parallel to the twin axis, being perpendicular to both the composition and symmetry planes, has symmetrical extinctions, and is optically indistinguishable from a normal twin with the same composition plane.

(2) The section normal to the twin axis coincides with the symmetry plane, hence the extinction angles are equal and at the same side of the composition plane, and the twin is invisible.

In Figs. 3, 4 and 5 the position of the symmetry plane of a twin is indicated by a horizontal line at a distance of 90° from the position of the twin axis. Thus, in Fig. 3 the symmetry plane of the Ala B twin is represented by the line marked $\perp a$. The intersections of the extinction curves with this line give the extinction angles of one of the twin individuals in the section normal to the symmetry plane. The extinction angle of the other individual is found by reversal of sign. If the section is not normal to the symmetry plane, the two points representing the twin individuals should be situated at equal distances on either side of the line representing the symmetry plane. Again, one of the extinction signs as found in the diagram should be reversed. The necessity of this reversal of sign is indicated by $\ominus$ after the name of the twin in the margin of the diagrams. Thus, Ala B $\ominus$ means that the positions of the individuals of an Ala twin should be symmetrical with regard to the line marked $\perp a$, while the sign of one of the two extinction angles thus found should be reversed.

In a similar way, the extinction angle of the section normal to the twin axis, in which the twin is invisible, is found along the line representing that axis. If the section is not normal to the twin axis, the positions of both twin individuals must be situated at equal distances on either side of the line representing this axis. The extinction angles thus found in the diagram are used without reversal of sign, which fact is indicated by $\oplus$ after the name of the twin in the margin of the diagrams.

Summarizing, we can state that the points of the diagrams indicating the optical properties of the individuals of a twin should be situated at equal distances on either side of:

1) the line representing the symmetry plane, with reversal of the extinction sign of one individual ($\ominus$);
2) the line representing the twinning axis, without any reversal of extinction sign ($\oplus$).

The Procedure of Twin Determination

With the aid of the three diagrams it is possible to determine the law of twinning in many cases. The procedure is essentially a trial-and-error method. Of course, simple twins, consisting of two individuals only, are the most likely to present difficulties. Generally speaking, the composition plane is easier to determine than the twin axis. It is well brought out in Fig. 3 that in most sections of not too Ca-rich plagioclase the Ala-B twin is nearly invisible. Could this be the reason that this twin is so rarely recorded? A discussion of the specific properties of each twinning law would be rather tedious: these properties follow from the more general considerations presented and from the diagrams. An exception will be made for lamellar twinning and for twins cut approximately normal to *a*.

The determination of lamellar twinning

In the case of lamellar twinning, we are generally dealing with the albite, acline or pericline law. Of these, albite twinning is readily distinguished from the other two, while acline and pericline twinning often show little difference.

In plagioclase with less than 75% An, albite twins cut normal to the composition plane must show each of the following properties:

1) symmetrical extinctions (normal twin)
2) appreciable birefringence }
3) negative elongation } composition plane (010)

These properties are *never* simultaneously present in acline or pericline twins, as may be judged from Figs. 4 and 5. Over a large part of these diagrams the extinction angles are over 45° (positive elongation). In the remaining parts, either the birefringence is too low, or the extinctions are obviously asymmetrical or even situated at the same side of the composition plane (in the central part of the diagrams). These distinctions are an essential preliminary to all determination methods based upon the properties of albite or Carlsbad twinning. Thus far they have seldom been clearly stated in textbooks.

It appears from a comparison of Figs. 4 and 5 that the extinction angles and birefringences generally do not serve to distinguish between acline and pericline twins. As a rule, this distinction is only possible in sections where the angle between the (001) cleavage and the rhombic section is visible. As the interesecting line of both planes is the *b*-axis, this angle will be best visible in sections approximately normal to this axis, which is the twin axis of both laws. These sections are represented by the central parts of both diagrams: they have negative elongation with extinctions situated at the same side of the composition plane. The angle between the rhombic section and (001) for plagioclases of different composition may be read from Fig. 3. According to some authors smaller angles are also found, giving rise to twins intermediate between acline and "ideal" pericline twins. This discrepancy is due, at least partly, to a change in the chemical composition of the crystals after their formation.

Recognition of twins in the section normal to a

Sections normal to *a* are readily recognized. In plagioclase with less than 75% An the cleavage with negative elongation is (010), that with positive elongation (001). When the composition plane is (010) and the extinctions are symmetrical, the twin is an albite twin. Both twin individuals are normal to *a*, their (001) traces make an angle of 8°. When the composition plane is (010) and the extinction angles are different and situated on either side of this plane, the twin is a Carlsbad twin. When they are different and on the same side of the composition plane, it is an albite-Carlsbad twin. In both cases, only one individual can be normal to *a*: in the other individual no (001) cleavage should be visible.

When the composition plane is (001) and the extinctions are symmetrical, the twin is an acline or Manebach twin. The (010) cleavage traces in both individuals make an angle of 8° with each other. If the twin is lamellar, it is an acline twin. When, the other properties being equal, the trace of the composition plane is rather vague, while the (001) cleavage is distinctly normal to the section, the twin is a pericline twin.

In sections exactly normal to *a* the Ala twins are invisible, *a* being their twinning axis. In sections slightly differing from that position these twins become visible by small differences in extinction angle. The extinctions are always on the same side of the composition plane. Characteristically, the transverse cleavage-traces or composition planes of other twins are parallel in both individuals, because their direction is not altered by the twinning operation.

The Aid of the Universal Stage

The method has thus far been outlined for use without the universal stage. Yet it will be clear that this accessory is of great value if a systematical investigation of feldspar twinning is undertaken. With the aid of the universal stage it will be possible to bring the composition plane of most twins in the vertical NS position. On turning on A4 (or OEW) the behavior of the twin in the zone normal to the composition plane becomes evident at once. The elongation occurring in this zone may be judged from a rotation around A4 with the table in the 45° position.

Furthermore, sections may be made normal to *a*, to the twinning axis or to the symmetry plane of the twin. In favorable cases, these procedures will lead immediately to the composition as well as to the law of twinning.

When the composition plane is irregular, or when the results prove to be ambiguous, recourse can still be made to the zone method of Rittmann (1929) or to the method of Emmons and Gates (1939), where the twin axis, found in a similar way with a 5-axis stage, is subsequently plotted on a Wulff net.

Sources and Acknowledgments

To my knowledge the kind of diagram proposed here was first used by Köhler (1923), as far as the extinction angles are concerned. By folding the diagram of Fig. 3 along the line marked *c*, this author obtained a valuable chart for the determination of the composition of plagioclase from the corresponding extinction angles of the Carlsbad twin.

Figs. 3 and 4 were newly constructed according to data compiled by van der Kaaden (1950, p. 46, 47). The extinction angles of Fig. 5 were found with the aid of the Fresnel construction on the Wulff net, starting from data compiled by Reinhard (1931, p. 114*). The curves were drawn by rather rough interpolation between the measured points: no great precision should be expected. The diagrams should be used in a qualitative rather than a quantitative way. The birefringences in all diagrams were taken from the charts of Nieuwenkamp (1948).

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* The plagioclases with 4, 29, 64 and 97% An are omitted as they belong to the high-temperature form. N.B. In the table of p. 114 the symbols (100) and (001) should be reversed.

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