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PLAGIOCLASE DETERMINATION WITH THE AID OF THE EXTINCTION ANGLES IN SECTIONS NORMAL TO (010). A CRITICAL COMPARISON OF CURRENT ALBITE-CARLSBAD CHARTS

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ABSTRACT. The chart type proposed by Köhler (1923) is the best adapted for the determination of the anorthite content of plagioclase in combined albite-Carlsbad twins cut normal to (010). Once the orientation of the section is known, one extinction angle suffices for the determination. The charts here presented are redrawn after Köhler according to data of van der Kaaden, which, for the time being, are the most complete available.

OUTLINE OF THE DETERMINATION METHOD

The anorthite content of plagioclase can be determined by measuring the extinction angles $X' \wedge (010)$ of combined albite and Carlsbad twins in a single section normal to the composition plane. Such sections should fulfil the following requirements:

a. *The elongation with regard to the composition plane must always be negative if the An-content is below 70 percent.*[1]
b. *All twin individuals must show distinct birefringence if the An-content is below 80 percent.*
c. When the stage with crossed nicols is turned, the twin individuals must show at least three different extinction positions for X′.
d. The albite twin is generally lamellar. If the section is exactly normal to the composition plane, the lamellae must show symmetrical extinctions. This means that the lamellae must be invisible when the composition plane is in the 0° or 45° position with regard to the cross hairs.
e. The Carlsbad twin is generally simple. In sections normal to the composition plane the extinction positions are usually asymmetrical. This means that the twin will as a rule be visible in the 0° or the 45° position by a difference in brightness of the interference colors of the two individuals. Usually, this difference is best visible in the 45° position: in the 0° position the effect of different extinction angles is often largely compensated by different birefringences, so that equal illumination results.

It is interesting to note that these criteria do not serve to distinguish between Carlsbad and Ala B twins. The latter twin type, however, is much rarer. *Because of its more nearly symmetrical extinctions it is more liable to remain unobserved when occurring together with albite lamellae.*

It is the pair of extinction angles occurring in a Carlsbad twin cut normal to (010) that is often characteristic for a specific An-content. The albite lamellae are chiefly used as an aid for the twin recognition. When the Carlsbad composition plane is irregular, the albite lamellae may serve to indicate the (010) direction. They also provide a means for using sections that are not

[1] The parts that are printed in italics are not generally taken into consideration. Most of them are treated more fully in another paper (Tobi, 1961).

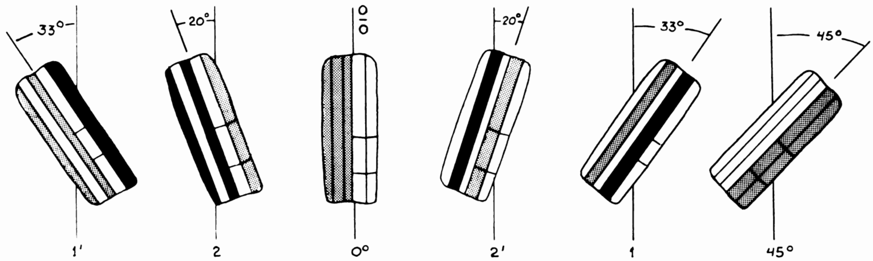


Fig. 1. Appearance of a combined albite-Carlsbad twin on turning the stage with crossed nicols. The Carlsbad individual at the right is oriented normal to a.

1-1′: extinction positions of albite lamellae in Carlsbad individual at the right.

2-2′: extinction positions of albite lamellae in Carlsbad individual at the left.

The albite lamellae "disappear" in the 0° and 45° positions, whereas the Carlsbad twin is visible in one or both these positions by a difference in brightness of the two individuals. In this particular section, the twins are also indicated by the (001) cleavage: the traces make an angle of 8° in the albite lamellae of the right Carlsbad individual and are invisible in the left individual.

exactly normal to the composition plane. When the composition plane is slightly tilted, one of the albite extinction angles will tend to become smaller, the other larger. Thus, when the angle between the two extinction positions is halved, the resulting angle will be almost equal to the extinction angle shown by the normal section.

The example given in figure 1 shows a section of a Carlsbad twin, one individual of which is oriented normal to a. This particular section offers an additional possibility for recognizing the twins: the transverse (001) cleavage traces of the corresponding albite lamellae differ in direction by 8°, whereas the other Carlsbad individual should not show the traces at all. *The Carlsbad law is the only type of twinning that changes the direction of the transverse cleavage in such an important degree.* Again, the cleavage traces allow of the distinction between positive and negative extinction angles: *if X′ passes through the acute angle between cleavage and composition plane, the extinction*

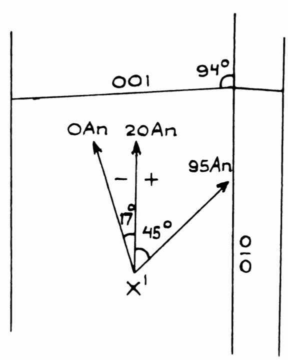


Fig. 2. Diagram of the extinction angles X′ ∧ (010) of plagioclase in the section ⊥a. Low temperature optics. Between 0 percent and 20 percent An the extinction angle passes through the obtuse angle of (010) and (001) and is called negative; above 20 percent An it passes through the acute angle and is called positive. Positive *elongation* with regard to (010) is found only for An-contents above 95 percent.

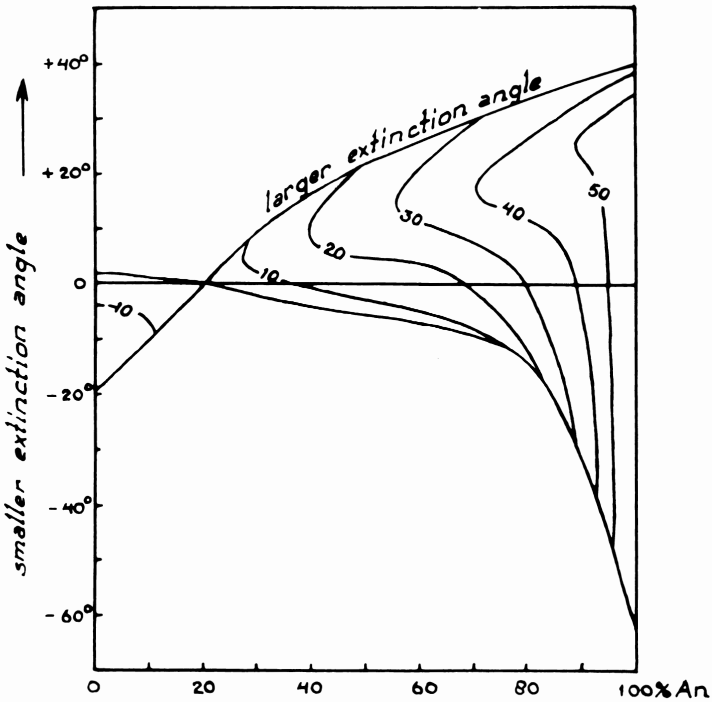


Fig. 3. Albite-Carlsbad chart according to Wright. Simplified, after Wright (1913).

is said to be positive, if it passes through the obtuse angle, negative.[2] In our example the extinction in the individual normal to a is positive. The extinction angle X′∧(010) of this particular section is, in itself, characteristic of the An-content, as is schematically indicated in figure 2. The elongation is seen to be negative up to an An-content of 95 percent. *This fact makes difficult the distinction between albite and acline lamellae in this section for An-contents above 80 percent.* In sections not normal to a the choice between positive and negative extinction must be made with the aid of other properties, for instance, the refringence.

THE CHARTS OF WRIGHT AND TROGER

To obtain the An-content from the two extinction angles of the Carlsbad twin, a chart is needed. The type of chart generally chosen to this end is the contour diagram.

One possibility is to plot the An-content along the abscissa and the smaller extinction angle along the ordinate. Following Michel-Lévy, this was done by Wright (1913). His chart is to be found in many textbooks (e.g., Winchell and Winchell, 1951, fig. 148; Kerr, 1959, fig. 13-30). A somewhat simplified form is given in figure 3. There exists no separate chart for high-temperature optics.

[2] For application of the Schuster rule—clockwise extinction positive, anti-clockwise extinction negative—the crystal should be regarded from the negative side of the a-axis, as is the case for the left individual of the albite twin shown in figure 2.

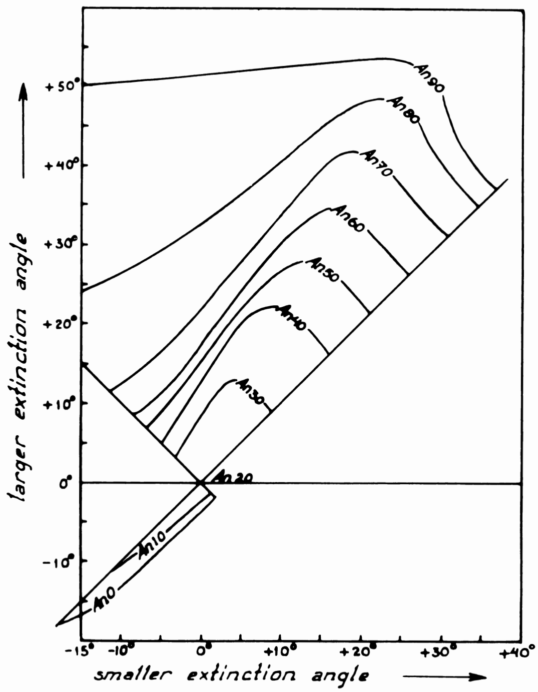


Fig. 4. Albite-Carlsbad chart according to Tröger. Low temperature optics. Simplified, after Tröger (1956). (Courtesy E. Schweizerbart, Stuttgart.)

A second possibility is to plot the two extinction angles along the coordinates. This way was chosen by Tröger (1956, p. 102). The chart is concerned only with low temperature optics. A somewhat simplified form is given in figure 4. The choice of the coordinates is perhaps more logical than in the first type, and the useful area of the chart is larger. In the original, the extinction angles to be used in the chart are not defined correctly. The smaller one is labeled extinction angle of the albite twin, the larger one extinction angle of the conjugated Carlsbad twin. Of course, it is quite irrelevant which of the two Carlsbad individuals has albite lamellae. In many cases, both of them have.

THE CHART OF KOHLER

Another type of chart, at first sight more complicated, was constructed by Köhler (1923).

The original idea might be from F. C. Calkins, who seems to have published a similar chart in 1915, based on what would now be described as a mixture of high- and low-temperature plagioclases. Köhler mentions this chart but did not have the complete publication (if any) at his disposal. We encounter the chart again in a review by Kennedy (1947). Here it is given as compiled by F. C. Calkins (1940) and modified by H. H. Hess (1941) in the region of the highly calcic plagioclases. Again, it seems to be composed of a mixture of high- and low-temperature optics, and again, the present author did not succeed in tracing the quotation back to the original publications (if any).

Köhler's chart may be thought of as having originated from figure 5. Here the An-content is plotted along the abscissa, the orientation of the section in the zone ⊥ (010) along the ordinate. The extinction angles are drawn in as contour lines. From a glance at this chart it is evident that it must be possible to determine the An-content from the maximum extinction angle to occur in this zone, which, indeed, is one of the current methods. The sections normal and parallel to a, which may be recognized under favorable circumstances, are indicated with drawn lines.

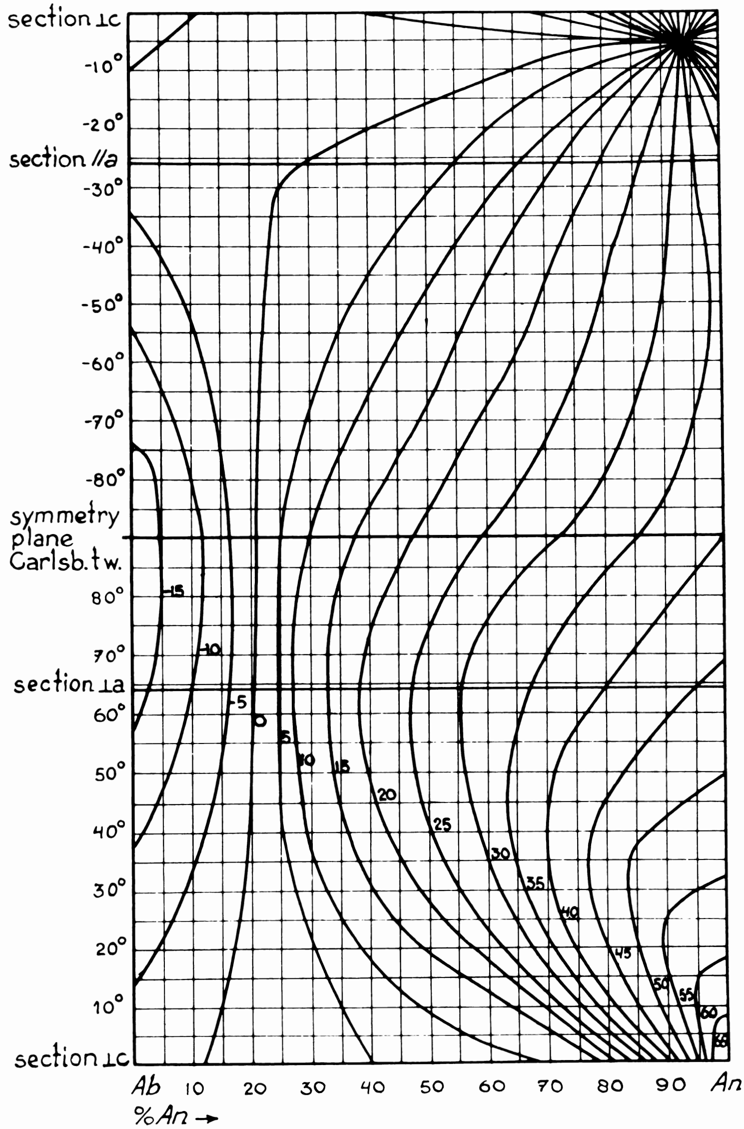
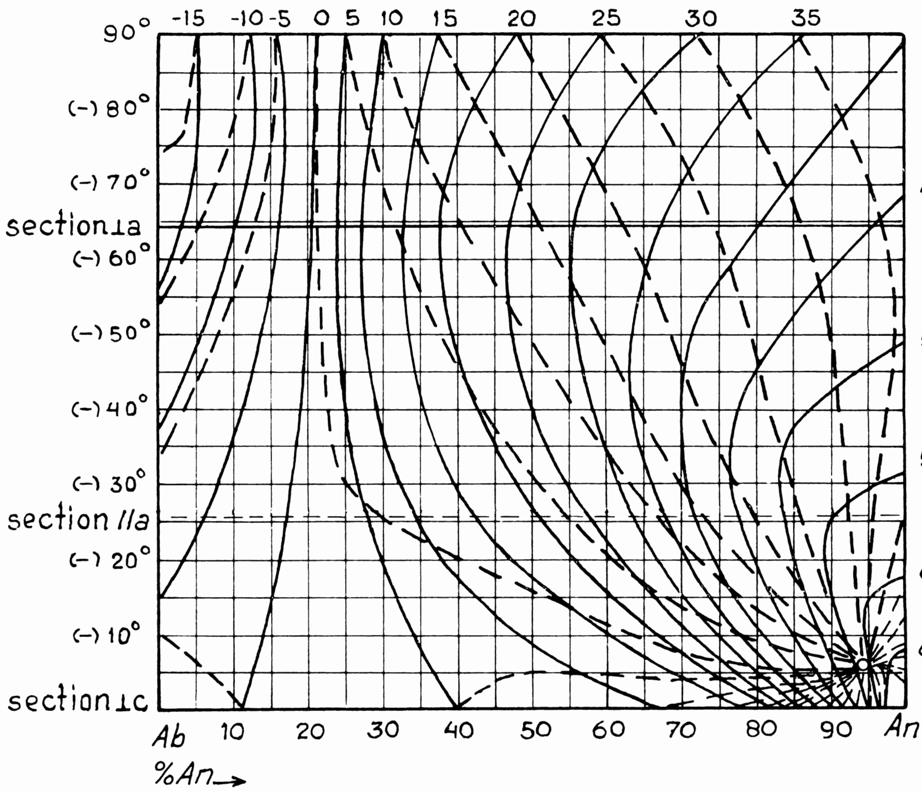


Fig. 5. Chart showing the extinction angles X′∧(010) in sections ⊥(010). Preliminary stage for the construction of the albite-Carlsbad chart after Köhler (1923). Drawn for low temperature optics from data of van der Kaaden (1951).



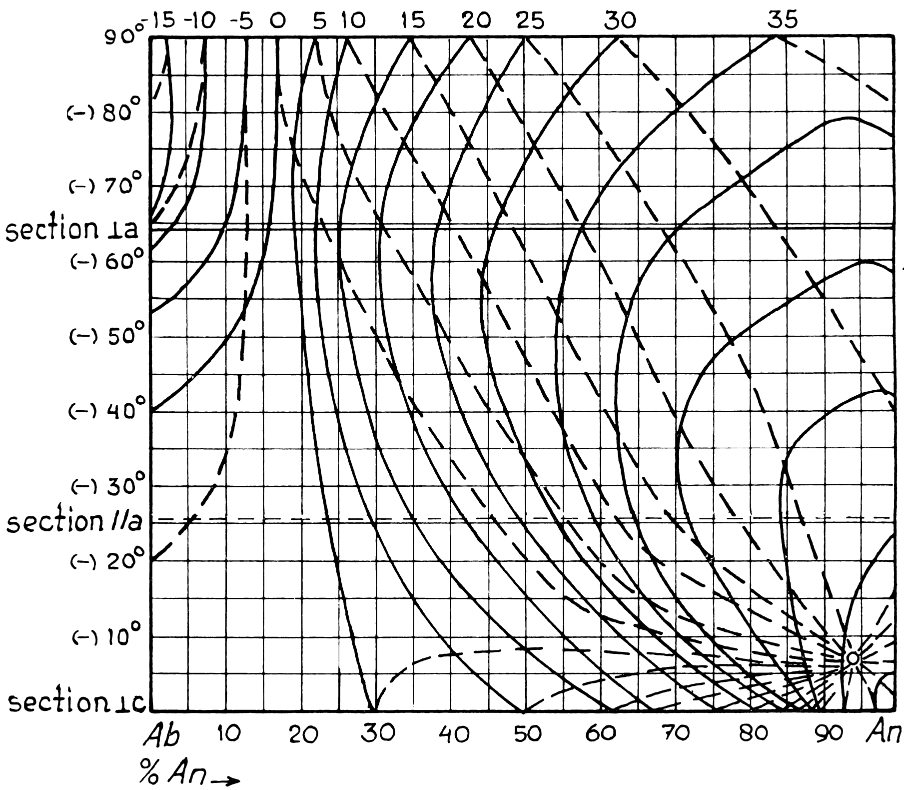
A

Fig. 6. Charts for plagioclase determination with the aid of extinction angles X′ ∧(010) in sections ⊥(010) oriented vertically. Solid line: larger extinction angle of Carlsbad twin, also for section ⊥ a and maximum extinction angle. Dashed line: smaller

Now which positions can the individuals of a Carlsbad twin occupy in the chart? First, to be able to use the method, we must take it for granted that the two individuals have the same An-content. Thus, their positions should fall on the same vertical line. Second, we should keep in mind that the c-axis is the twinning axis and that the symmetry plane of the twin must be normal to this axis. C-axis and symmetry plane are represented by the lines at the base and in the middle of the chart, respectively. *This means that the positions of the two individuals of a Carlsbad twin must always be situated at equal distances on either side of the line in the middle of the chart.* When the chart is folded according to this line, the positions of the two Carlsbad individuals will always coincide: we have obtained Köhler's chart (fig. 6).

HIGH AND LOW TEMPERATURE OPTICS

In drawing his chart, it occurred to Köhler that he obtained smooth curves only when intermediate and An-rich plagioclase phenocrysts deriving from lavas were left out of consideration (1923). This observation led to the discovery of the high-temperature modification in natural plagioclases (Köhler,



B

extinction angle of Carlsbad twin, also for section || a. A: Low temperature optics. B: High temperature optics.

1941). A special albite-Carlsbad chart for high temperature plagioclase in the range from 30 to 100 percent An was given by Tertsch (1942). Since then there has been much discussion about the subject. It is not yet clear what the differences exactly mean and to what extent transitional stages may occur (e.g., Muir, 1955).

In my opinion, this is no reason to ignore the high temperature form, as has been done in many textbooks. *When considering intermediate or An-rich plagioclase deriving from a lava, one will generally be nearer to the truth with the high temperature than with the low temperature data.* As will be seen from a comparison of figures 6A and B, the differences between the readings of the two charts may amount to about 10 percent An, which is too much to pass by willfully.

THE CHARTS HERE PRESENTED: SOURCES AND ACCURACY

The charts given in figure 6 were constructed anew by the present author, using data of van der Kaaden (1951, table 5). Although based on a comparatively small number of widely known chemical analyses, *the data compiled by* *van der Kaaden must be considered the most complete and the most reliable at this moment.*

The chart for low-temperature optics is based on chemical analyses already used by Reinhard (1931) with An-contents of 0, 13, 20, 25, 35, 52, 73, and 100 percent.

The chart for high-temperature optics is based on the "Linosa feldspars" with 35½, 45½, and 54 percent An (Köhler, 1941), on synthetic plagioclases with 70, 80, 90, and 100 percent An (Tertsch, 1942), and on an average of synthetic and heated natural plagioclases with about 0 percent An (Laves and Chaisson, 1950). The heated natural plagioclases with 3½, 17, and 26½ percent An used by Tertsch (1950) were rejected by van der Kaaden as being transitional stages.

It is not the place here to dwell at length on the accuracy of these data nor to compare the determination results with those obtained with other methods.

During the International Geological Congress in 1960 in Copenhagen, Burri stressed the desirability of renewed extensive research on the relations between chemical composition and optical properties of the plagioclases. As long as this work is not completed, the wisest thing to do is to base all charts and tables using the optical orientation of plagioclase on the same fundamental data. For this purpose the data of van der Kaaden, which also underlie the determination charts of Tröger (1956), should be chosen. In this way the results obtained by all workers will be directly comparable and easily rectified once the final data based on a sufficiently large number of accurate chemical analyses are known.

It appears from figure 6 that the Carlsbad extinctions are not favorable in the composition area of albite and oligoclase. This is not too serious, because the Carlsbad twin is found less frequently in these plagioclases. It is suggested to use here sections normal to a or to the indicatrix axes. *In the composition*

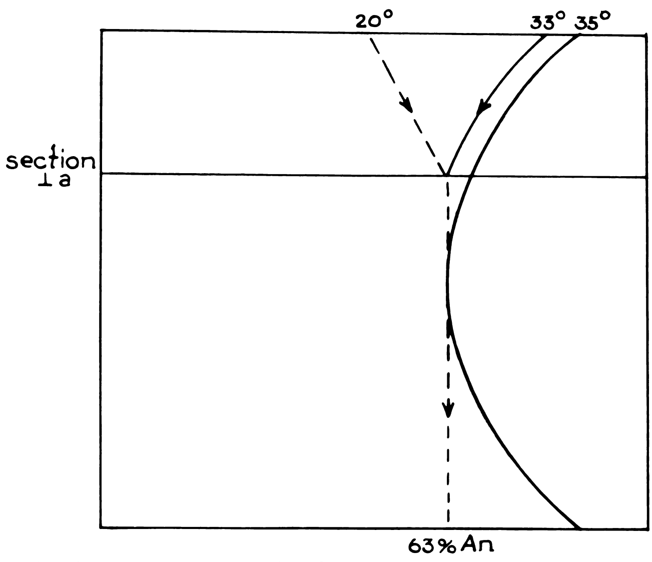


Fig. 7. Key for figure 6, drawn for the case of figure 1. The Carlsbad individual with extinction angle of 33° is oriented normal to a, so that the horizontal line representing that orientation must pass through the intersection of the extinction curves of the two individuals. The curve of the maximum extinction angle to occur with that An-content (35°) is also indicated. Low temperature optics.

area of intermediate plagioclase one should not use sections with Carlsbad extinction angles differing more than 15°.

MULTIPLE USE OF KOHLER'S CHART

First, it should be pointed out that the charts of figure 6 can be used equally well for sections normal to a. The An-content is then given by the intersection of the horizontal line representing that orientation and the solid curve of the corresponding extinction angle. When the section normal to a is part of a Carlsbad twin, the smaller extinction angle belonging to the other individual and represented by a dashed curve should pass through the same point. This is illustrated schematically in figure 7 for the case given in figure 1.

Second, the maximum extinction angle to occur with this An-content may also be read from the chart: it is represented by the extinction angle curve tangent to the vertical line denoting that An-content. In figure 7 the maximum extinction angle is found to be 35°. Of course, a universal stage would be needed to obtain it from the same section.

Third, when a Carlsbad twin is zoned, the crystallographic orientation of one individual will be the same for all zones. Thus, the intersections of the extinction angles corresponding to all zones must be on the same horizontal line. It should be pointed out that the method can be used here only when the zones pass unhampered through the composition plane of the twin. An example is schematically indicated in figure 8. *It will be perceived that one extinction angle suffices once the orientation of the section is known.* This is one of the important assets of Köhler's chart.

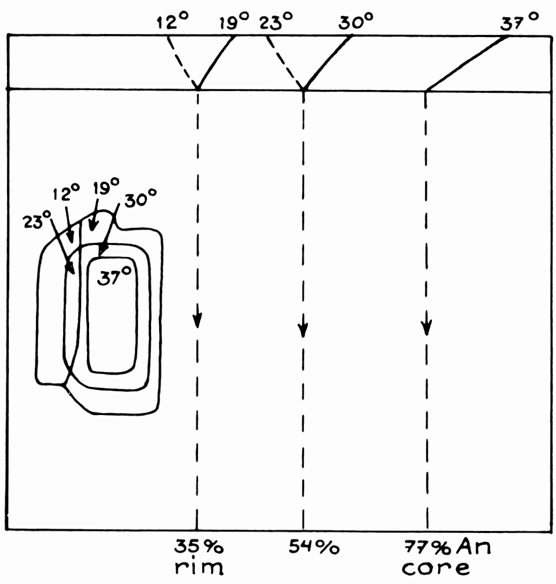


Fig. 8. Key for figure 6, drawn for the case of a zoned Carlsbad twin as indicated schematically in the inset. Once the orientation is known, a single extinction angle suffices to determine the An-content, as is the case with the core of our example. For clarity, the albite lamellae are omitted. High temperature optics.

In both cases, the chart provides an extra check on the accuracy of the determination. Under favorable circumstances, the degree of fitting may be helpful in choosing between high- and low-temperature optics.

Plagioclase microlites in lavas are often elongated according to a. Sections parallel to this axis, and at the same time showing sharp albite lamellae, must have the orientation indicated in the chart by a dashed horizontal line. The extinction angles found in this section are the intersections of this line with the dashed extinction curves.

CONCLUSIONS AND SUMMARY

Burri rightly stated that a new exhaustive study should be made of the optical properties of the plagioclase group, based upon a large number of chemical analyses. For the time being, however, the most complete data are those of van der Kaaden. It is suggested that these should be used universally for all charts and tables based upon the optical orientation. This would facilitate direct comparison and eventual correction of An-contents determined with this method.

When albite or Carlsbad twinning are used for the determination, it is necessary to know how they are recognized. The rules for their recognition are often not sufficiently stressed in textbooks.

When determining plagioclase by measuring extinction angles, it makes sense to distinguish between high and low temperature optics.

For all current methods based upon the extinction angles in the zone normal to (010), the chart type proposed by Köhler offers the best solution. The chart gives a clear account of the extinction angles found in the whole zone for all members of the plagioclase group. Hence, it gives more insight into the possibilities, the limitations, and the relations of the various methods. Results obtained with these methods can be plotted, compared, and checked in the same chart. The fact that the orientation of the section is brought into the chart is especially useful for the determination of zoned Carlsbad twins. Most of these advantages have been stressed before. Yet it seems important to bring them again under the eyes of all who are interested in plagioclase determination, writers of textbooks not excluded!

The charts presented in this paper were newly constructed for high- and low-temperature optics according to the data of van der Kaaden.

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