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10. THE DETERMINATION OF PLAGIOCLASE FELDSPARS

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INTRODUCTION

The material included in this paper was brought together for the use of students in the petrographic laboratory of Harvard University and has been in use in this laboratory for a year and a half with concordant results. The curves agree closely with those given by Calkins,[1] and by Wright[2] but do not agree with those given by Iddings and other textbooks on rock minerals. As the curves by Calkins have not been published and those by Wright are not now readily accessible it was thought that this material would be of use to petrographers. Most of the data have been plotted from the stereographic projections given in the memoir of Duparc and Reinhard. In addition to the curves a discussion of the error in measurements is given. The writer is indebted to professor E. S. Larsen for his generous assistance in the preparation of this manuscript.

No attempt has been made to prepare curves for the determination of the amounts of $KAlSi_3O_8$ in solid solution as the data available are not sufficient.

Duparc and Reinhard[3] have shown that the relative amounts of $NaAlSi_3O_8$, $KAlSi_3O_8$, and $CaAl_2Si_2O_8$ in the plagioclases can be determined by locating the indicatrix with respect to the crystallographic axes by the aid of a theodolite microscope. The principal

[1] Calkins, F. C., unpublished photostats.

[2] Wright, F. E., A graphical plot for use in the microscopical determination of the plagioclase feldspars, *Am. Jour. Sc.*, **36**, 540–542, (1913).

[3] Duparc, L., and Reinhard, M., La détermination des plagioclases dans les coupes minces, *Mem. Soc. de phys. et d'hist. nat. Genève*, **40**, (1924).

Duparc, L., and Reinhard, M., Les methodes de Fédorof et leur application a la détermination des plagioclases, *Bull. Suisse de Min. et Pet.*, **III**, 1924.

planes of the indicatrix are determined from interference figures, or by locating the optic axes; the crystallographic axes from cleavage, twinning planes, or crystal boundaries. The data obtained are then plotted on a sphere or stereographic projection using the base, (001), as the equatorial plane. For ordinary thin section work this method probably will not commend itself to petrographers on account of the time and technique involved, but it will be of value for special studies, for example in determining the optical orientation of any triclinic mineral.

In the following pages not all of the methods of determining the plagioclases are discussed but only those that have been found most useful in the Harvard laboratory. The methods are described in the following order and the letter preceding the method refers to the corresponding curves on the diagrams.

A. Index of refraction.
B. Density.
C. Axial angle and optical character.
D. Extinction angles on the side pinacoid.
E. Extinction angles on the section perpendicular to the base and side pinacoid.
F. Extinction angles on the basal section.
G. Extinction angles in the zone perpendicular to the side pinacoid, (Michel Lévy statistical method).
H. Extinction angles on combined albite-Carlsbad twinned plagioclases in the zone perpendicular to the side pinacoid.
I. Extinction angles in microlites.
J. Extinction angles in sections perpendicular to the α-vibration direction.
K. Extinction angles in sections perpendicular to the β-vibration direction.
L,M. Extinction angles in sections perpendicular to the γ-vibration direction.

The extinction position referred to is in all cases the vibration direction of the ray with the lower index of refraction in the section. In crystallographically oriented sections it is denoted by α'. This position can be found easily by means of the gypsum plate. The extinction angle is measured from this vibration direction to some crystal direction, commonly the trace of the side pinacoid.

A. Index of Refraction (See Fig. 2)

The determination of one of the three indices of refraction, (α, β, or γ), by the immersion method is one of the quickest and most reliable methods for determining the feldspars. It is not sufficient to measure a random index of refraction but one of the three principal indices should be measured. An approximate determination can commonly be made by comparing the indices of refraction of the feldspar with that of Canada balsam, or with quartz, or some other known mineral. The index of refraction of balsam is commonly near 1.539, but it may vary considerably, especially in old slides. It has been found as high as ϵ of quartz (1.554). It is therefore best to check the balsam against ω of quartz or against some other mineral with known index of refraction before using it as a standard of comparison.

B. Density (See Fig. 3)

The curve for density is approximately a straight line. The variation with composition is considerable, about 0.002 for each percent of anorthite, and, under favorable circumstances, a density measurement gives a good determination of the feldspar. However, most material is not suitable for rapid density determination on account of the difficulty of getting coarse fragments that are homogeneous, unaltered, and free from gas or other inclusions.

C. Axial Angle and Optical Character (See Fig. 3)

The optical character of the plagioclase feldspars changes sign four times, and hence can be used to divide the plagioclases into four groups and check determinations made by other methods.

CRYSTALLOGRAPHICALLY ORIENTED SECTIONS

D. Side Pinacoid (See Fig. 2)

This section can be recognized thus:

(1) Albite twin lamellae are absent.

(2) Basal cleavage planes are approximately perpendicular to this section.

(3) Zoning is conspicuous, with equal illumination of the zones at +40.5° measured from the basal cleavage.

(4) Except for the more calcic feldspars the γ-bisectrix gives a more or less uncentered figure.

(5) The geometric outline is distinctive, and commonly a parallelogram with an acute angle of 64° (fig. 1). Other faces frequently modify this outline, such as ($\bar{1}01$), ($10\bar{1}$) and ($20\bar{1}$), ($\bar{2}01$). ($\bar{2}01$) makes an angle of about 98° with the base.

Even when the outlines are anhedral, the zoning, which is best shown on this face, and which follows the crystal outlines, may give the necessary clue to determine the crystallographic orientation.

Schuster defined the extinction angle as positive when the smaller extinction angle, [$\alpha' \wedge$ trace of (001)], is in the obtuse angle

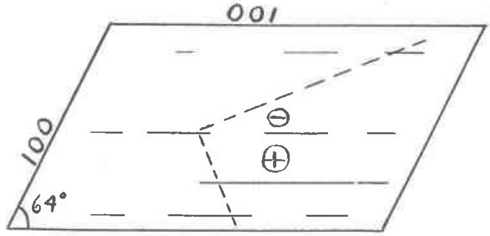


FIG. 1

between (100) and (001), and negative when it is in the acute angle.

Where zoning is present, the extinction angles on the same side of the zero position, (which is the trace of the basal cleavage), as the position of equal illimination of the zones are positive. Probably without exception in igneous rocks, the zones become more sodic toward the border, though some rhythmic recurrence of zones is common. In this section the extinction of α' and the composition can be determined for each zone.

The slope of this curve is fairly uniform for feldspars ranging from 0% to 70% anorthite, and gives a variation of about 0.7 degree for each per cent anorthite. The curve flattens for feldspars more calcic than 70% anorthite, giving a difference of about 0.25 of a degree for each per cent anorthite.

E. The Section Perpendicular to the Base and Side Pinacoid (See Fig. 2)

This section can be recognized thus:

(1) It ordinarily has a well-formed outline.

(2) The albite twins have symmetric extinction, with equal illumination of these lamellae at 0° and 45°.

(3) The suture lines of the twin and cleavage plane (010) and the cleavage plane (001) form an angle of about 86°, and the planes are perpendicular to the section. To determine whether or not a cleavage or twinning plane is perpendicular to the section focus the telescope tube up and down, and observe whether the plane remains stationary with respect to the cross-hairs or moves laterally. If it moves laterally it cannot be parallel to the line of collimation of the telescope.

(4) A negative bisectrix is more or less centered on this section in the feldspars of intermediate composition.

This extinction position, α', is measured from the trace of the albite twinning plane. The sign of the extinction is positive when it is in the acute angle formed by (001) and (010), and negative when in the obtuse angle.

This is one of the best sections for determining the composition of a plagioclase, because the variation of the extinction angle with composition is about one degree for each per cent of anorthite in the range from 0% to 35% anorthite. In feldspars more calcic than 35% anorthite the curve flattens out and gives a variation of about 0.5 of a degree for each per cent anorthite. A considerable error in the orientation gives small errors in composition for feldspar ranging from 10 to 50 per cent of anorthite, and the orientation of these sections can be determined fairly accurately. Such a method is therefore good for feldspars ranging from $Ab_{90}An_{10}$ to $Ab_{50}An_{50}$.

F. Basal Section (001) (See Fig. 2)

This section cannot be readily recognized in the thin section but as (001) is the most perfect cleavage the powdered grains used in an immersion to test the index of refraction tend to lie on this face. The most favorable grains will lie on a cleavage face and will have another cleavage face as their upper surface, and hence will be of uniform thickness and will give uniform interference colors. Step-like breaks in the cleavage are also common, giving abrupt changes in the interference colors. This face is normal to the albite twin lamellae, which will therefore have symmetric extinctions, and have equal illumination at 0° and 45°.

The curve is very flat between albite and andesine-labradorite, (50% An), a difference of one percent in anorthite giving a variation of about 0.2 of a degree. For feldspars more calcic than 50% anorthite the curve is very good, giving, for each percent difference in anorthite a variation of about 0.7 of a degree. The error due to error in orientation is relatively large, especially for feldspars ranging from $Ab_{50}An_{50}$ to $Ab_{20}An_{80}$ in composition. For such feldspars the maximum error in composition is 13% anorthite for a deviation of 10° in the orientation of the section. This method is then not of much value for determinative work unless the section be oriented very accurately.

MAXIMUM EXTINCTIONS IN CERTAIN ZONES

G. The Zone Perpendicular to the Face (010), that is Perpendicular to the Composition Plane of the Albite Twins (See Fig. 3)

This zone can be recognized easily by the fact that the twin individuals 1 and 1′ are equally illuminated at 0° and at 45°. If the orientation is perfect, the extinctions of these individuals are symmetrical and the traces of the composition planes form sharp lines. If the telescope tube be focused up and down, these lines will be found to remain stationary with respect to the cross hairs. If the section is not perpendicular to (010), the lines will appear to be blurred and to move sideways.

The extinction position, α', is measured from the albite twin plane. When the section is not perpendicular to (010) the extinction angles on the individuals 1 and 1′ will not be the same, and the mean of these two readings will then be used. The maximum extinction angle obtained in this way is then referred to curve G, which will give the composition of the feldspar.

Since the slope of the curve is steep, a deviation of 10° in orientation gives a maximum error of 2% anorthite for feldspars ranging from albite to $Ab_{30}An_{70}$, and the section can be oriented fairly accurately into the zone, this is one of the best determinative methods.

H. Combined Albite-Carlsbad Twinned Feldspar; (Zone ⊥ (010)) (See Fig. 4)

These sections give two sets of twin lamellae: 1, 1′; 2, and 2′. When the plane of the section is perpendicular to (010) then 1, 1′, 2, and 2′ will all have equal illumination at 0° and 45° to the planes of vibration of the nicols. At any other angle the four twin lamellae will be unequally illuminated.

The extinction angles are plotted for the zone perpendicular to (010). When such a section is found 1 and 1′, (2 and 2′), will have equal angles of extinction. When the section is not perpendicular to (010) then the four extinctions will all be unequal. The mean reading, (α'_λ trace of (010)), of 1 and 1′, and of 2 and 2′ are taken, the smallest angle is read along the vertical line of the diagram H, and the other along the isogonic curves. That is to say, the composition of the feldspar is read from a point where the horizontal line representing the smaller extinction angle meets a curved isogonic line which corresponds to the larger extinction angle.

For a plagioclase which has a composition $Ab_{80}An_{20}$ the (010) plane is one of the principal planes of the indicatrix and hence Carlsbad twinning cannot be seen in the thin section. The difference in the extinction angles of 1, 1′ and 2, 2′ increases with increasing amount of anorthite.

The two values for the extinction angles on each Carlsbad twin will give, in general, two values for the feldspar, hence this method must be supplemented by some other method such as an approximate estimate of the index of refraction, in order to tell which of the two values is the correct one.

Since a relatively small error in orientation means an appreciable error in the determination of the feldspar, these sections should be oriented accurately.

I. Microlites (See Fig. 2)

Curve I gives the maximum extinction angle for microlites elongated parallel to the crystallographic axis *a*. It is not possible to distinguish between positive and negative extinction angles so that, for sodic feldspars, the index of refraction test against Canada balsam must be used to determine on which side of $Ab_{70}An_{30}$ the feldspar lies.

The position of extinction, α', is measured from the direction of elongation of the microlite, and the maximum angle obtained is used to read off the composition of the feldspar on curve I.

OPTICALLY ORIENTED SECTIONS

J. Sections Perpendicular to α (See Fig. 3)

This section is located by getting a centered interference figure. The extinction position used is the β–vibration direction, and the angle is measured from the trace of the (010) plane.

These sections show clearly all the twinning phenomena. The albite twin lamellae of feldspars ranging in composition from 0 to 35 percent anorthite will give symmetric extinction angles on this section. These same feldspars will have the basal cleavage approximately perpendicular, i.e. within $\pm 10°$, to this section. This curve is good only for feldspars ranging from albite to $Ab_{50}An_{50}$, and is identical with the curve of maximum extinction angles in the zone perpendicular to (010) in the range from albite to $Ab_{65}An_{35}$.

This method gives good determinations for the sodic feldspars since the extinction angles change rapidly with change in composition, while the error in composition due to an error in orientation is small.

K. Sections Perpendicular to β (See Fig. 3)

Sections perpendicular to the β index can be recognized easily as they will show the maximum birefringence, and in convergent light a centered flash figure.

The position of extinction, α, is measured from the trace of the albite twin plane in the section.

This curve is only applicable to the calcic feldspars in which the anorthite content exceeds 35% as the curve becomes very flat for the sodic feldspars and reaches a maximum at about $Ab_{80}An_{20}$. An error of 10° in the orientation gives a maximum error of 10% anorthite for the calcic feldspars, and since this section cannot be oriented accurately this method is not of much value.

L. M. Sections Perpendicular to γ (See Fig. 3)

This section is located by getting a centered interference figure. The extinction position used is the α-vibration direction.

In the alkaline feldspars, ranging between albite and $Ab_{50}An_{50}$, the sections perpendicular to γ will not show albite twinning; the extinction position should then be measured from the trace of basal cleavage and read on curve M. These sections in feldspars which are more calcic then $Ab_{50}An_{50}$ will show the (010) twinning planes as soft lines, and extinction should be measured from them and the composition read from curve L.

ACCURACY OF DATA

Assuming that: (1) the feldspar consists only of a solid solution of albite and anorthite, and (2) the extinction curves are accurate; then the error in determination would lie in (1) the error in measuring the extinction angle, and (2) the error in orientation of the section measured.

In ordinary practice the average error in reading an extinction angle will be plus or minus one degree. This does not mean that the ordinary petrographer can not determine the extinction angle closer than this but merely that an increase in accuracy would mean such a large increase in time and technique that it is not ordinarily sought. An error of 1° in angle gives an error in composition of from 1 to 2% anorthite in the determination, an amount which is, in most cases, considerably less than the error due to imperfect orientation.

The following table gives the error in percentage of anorthite for various plagioclase feldspars caused by deviations of 10°, 20°, and 30° in orientation from the section desired, for the methods E, F, G, J, K, and H.

TABLE I

E. ERROR IN ORIENTATION FROM SECTION ⊥(001) (010)

PER CENT OF ANORTHITE	10°		20°		30°	
	Max.*	Avge.*	Max.*	Avge.*	Max.*	Avge.*
0.5% An.	7	4	10	5	12	10.5
13	1	1	2	1	5	3
20	0.5	0	3	1	8	5
25	1.5	1	2.5	1	4	2
35	2.5	1	5	4	16	9
52	4	1	5.5	4	15	8
73	8	5	15	9	20	10
97	12	10	19	15	28	19

F. ERROR IN ORIENTATION FROM BASE (001)

PER CENT OF ANORTHITE	10°		20°		30°	
	Max.*	Avge.*	Max.*	Avge.*	Max.*	Avge.*
0.5	16	11	27	19	31	21
13	5	5	13	9	20	10
20	4	2	12	6	23	12
25	1	0.5	8	3	22	11
35	7	1	7	3	22	12
52	13	6	16	5	20	10
73	13	6	22	9	28	15
97	3.5	2	74!	8	74!	13

G. ERROR IN ORIENTATION FROM THE SECTION THAT GIVES THE MAXIMUM EXTINCTION IN THE ZONE PERPENDICULAR TO (010)

PER CENT OF ANORTHITE	10°		20°		30°	
	Max.*	Avge.*	Max.*	Avge.*	Max.*	Avge.*
0.5% An.	3	1	7	3	9	7
13	0.5	0.5	1.5	1	4	3
20	0.5	0	1.5	0.5	3.5	1
35	2	1	7	4	17	10
52	2	1	7	5.5	13	11
73	2	1	10.5	4	42!	9

* Max. (avge.) means the maximum (average) error in composition expressed in percentage of anorthite.

J. Error in orientation from the section perpendicular to the α-vibration direction

Per cent of anorthite	10°		20°		30°	
	Max.*	Avge.*	Max.*	Avge.*	Max.*	Avge.*
0.5% An.	2	1	5	3	11	7
13	0.5	0.5	1	1	4	1.5
20	0.5	0.5	2	2	8	3.5
35	1.5	0.5	8	5	28	10
52	5	4	16	11	29	12
73	44	37				

K. Error in orientation from the section perpendicular to the β-vibration direction

Per cent of anorthite	10°		20°		30°	
	Max.*	Avge.*	Max.*	Avge.*	Max.*	Avge.*
35% An.	10	5				
52	6	4	10	7	16	10
73	8	4	16	7.5	19	12
97	10	9	19	12.5	29	20

H. Error in orientation from the zone (010). (Combined albite-Carlsbad method)

Per cent of anorthite	10°		20°		30°	
	Max.*	Avge.*	Max.*	Avge.*	Max.*	Avge.*
35% An.	10	3	23(41)	9	29(48)	9
52	6(33)	1	22(34)	8	30(34)	14.5
73	8(14)	3.5	27	7.5	27	11

The following table gives in columns 2 and 3 the number of grains that must be examined in order that, on the average, one will have an error of orientation not greater than that listed in column 1. This error of orientation is given as the angle of deviation from the section that gives the correct extinction angle.

* Max. (avge.) means the maximum (average) error in composition expressed in percentage of anorthite.

TABLE II

NUMBER OF RANDOM GRAINS NECESSARY

ACCURACY OF ORIENTATION	FOR ALL THE EXTINCTION CURVES EXCEPT COMBINED ALBITE-CARLSBAD TWINS	FOR THE COMBINED ALBITE-CARLSBAD METHOD
2°	1642	29
4°		14
6°	182	9
10°	65	6
20°	17	3
30°	7.5	2

For optically oriented sections, if the direction of vibration emerges on the edge of the field, then the deviation from the correct orientation will be about 30° for the general types of petrographic microscopes. If the vibration direction emerges about two-thirds of the distance from the center to the edge of the field then the deviation will be between 15° and 20°.

Assuming now that (1) an average thin section has a diameter of 15 millimeters and that plagioclase feldspar makes up half the slide, and (2) that the best feldspar section in the slide for a certain method of determination, (excluding the method for combined albite-Carlsbad twinning), is chosen for the determination; then the average deviation or error in orientation from the section desired of the best section in the slide, i.e. the statistical minimum deviation in orientation, is given in the following table for various grain sizes which correspond to medium grained rocks.

TABLE III

DIAMETER OF GRAIN IN MILLIMETERS	ERROR IN ORIENTATION OF THE BEST SECTION IN THE SLIDE, GIVEN AS THE DEVIATION FROM THE SECTION TO WHICH THE TRUE ANGLE OF EXTINCTION CORRESPONDS
1	8°
2	15°
3	23°
4	31°
5	35°

Thus when using, for example, exclusively the Michel Lévy statistical method on medium-grained rocks the best sections will have an error in orientation of about 20°. The following table IV taken from table I gives the error in composition to be expected from such a section, and since this is one of the best sections for determinative work the other methods will, in general, have a larger error in composition, the values for which can be obtained from Table I.

TABLE IV

Feldspar in per cent of anorthite	Maximum error in per cent of anorthite, due to orientation ± reading	Average error in per cent of anorthite
0.5	7 ±2	3 ±2
13	1.5±1	1 ±1
20	1.5±0.5	0.5±0.5
25	7 ±0.5	4 ±0.5
35	7 ±1.5	5.5±1.5
52	10.5±2	4 ±2

This error in orientation will, of course, be decreased when several methods are used conjointly and the best section of several methods is utilized.

The error in orientation from the zone (010), (the method for combined albite-Carlsbad twinning), assuming that all the feldspar grains display combined albite-Carlsbad twinning and that the best of the sections is chosen, is given in column 2 of the following table for various grain sizes, corresponding to the medium-grained rocks, and which are listed in column 1.

TABLE V

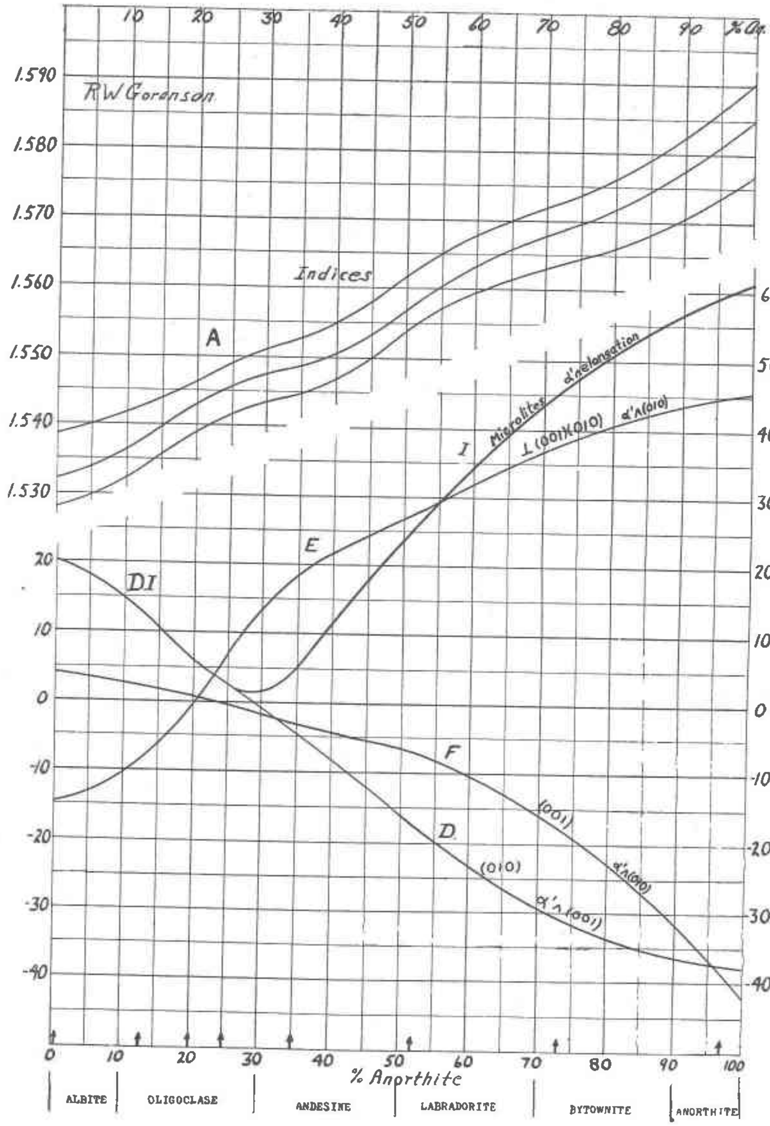
Diameter of grain in millimeters	Error in orientation of the best section, i.e. deviation from the zone perpendicular to (010)
1	0
2	2°
3	5°
4	8°
5	13°

Thus the error in orientation for this zone will be in general about 5° or less, and the best section can be found easily, (see the discussion on this method). This is the reason that the method has any determinative value, since an error on 10° in orientation means an error in composition of from 6 to 10% anorthite.

By the ordinary rapid immersion method, using liquids calibrated to 0.001 and 0.01 apart, the indices of refraction can be measured with a probable error of less than ± 0.003. An error of ± 0.003 in the β index means an error in composition of from 4 to 9% anorthite. To be sure that the error in composition is less than 5% the index must be determined to ± 0.001.

One occasionally finds that an author has stated the composition of a feldspar determined by these methods to a tenth of one percent anorthite which is ridiculous since, in ordinary practice, the error in determining the composition is about 5% or more of anorthite.

If care is used in choosing the best section in the slide and in measuring the extinction angles, and if several of the best methods are used conjointly, one should be able to bring the error in composition to within 5 per cent anorthite. That is to say, if these precautions are observed, the composition of the feldspar can be stated to ± 5% anorthite with a fair amount of certainty.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R W Goranson
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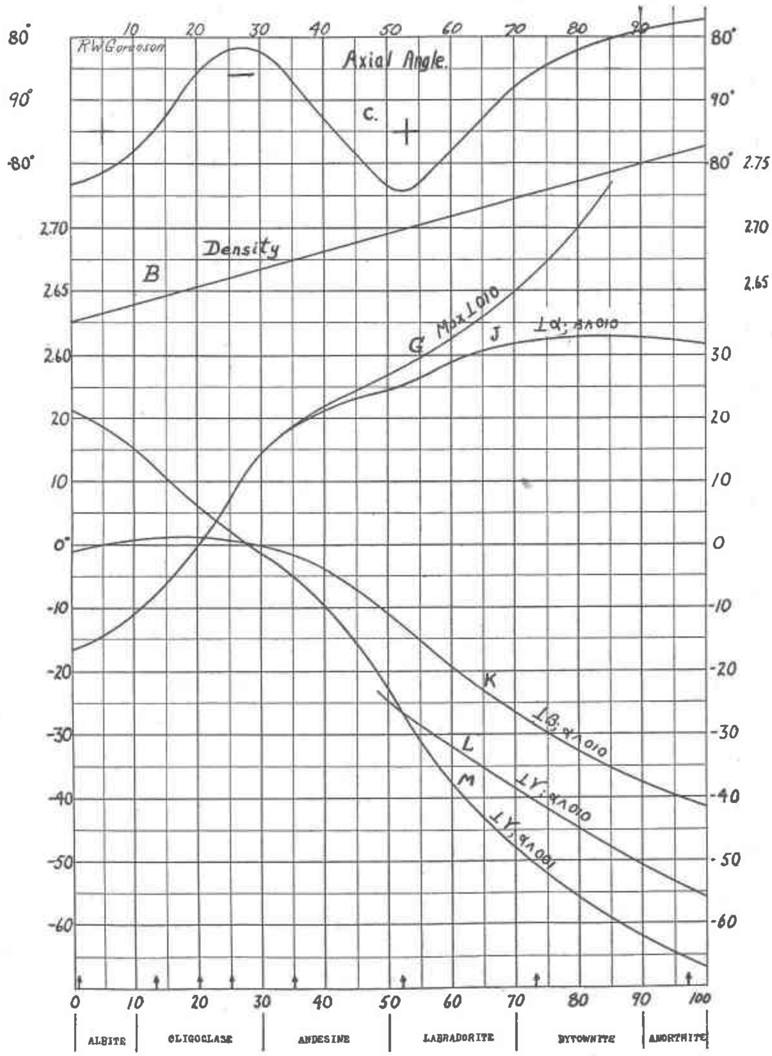
ALBITE
OLIGOCLASE
ANDESINE
LABRADORITE
BYTOWNITE
ANORTHITE

FIG. 2


R.W. Gorenson
Axial Angle.
C.
Density
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ALBITE
OLIGOCLASE
ANDESINE
LABRADORITE
BYTOWNITE
ANORTHITE

FIG. 3

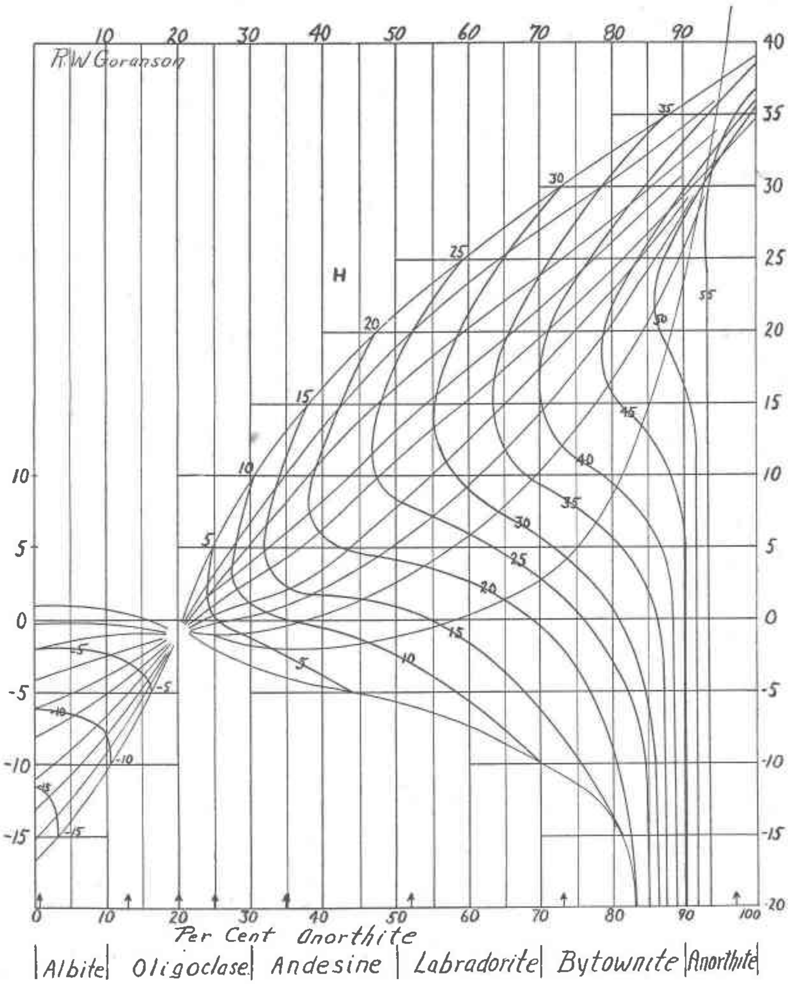
R.W. Goranson
H
Per Cent Anorthite
Albite
Oligoclase
Andesine
Labradorite
Bytownite
Anorthite

FIG. 4