A dispersion method of determining plagioclases in cleavage-flakes.

(*With Plate I.*)

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[Read June 19, 1923.]

Introduction.

RECENTLY H. E. Merwin employed an improved immersion method for determining refractive indices to identify certain salts of the system $Fe_2O_3-SO_3-H_2O$. In the present paper is described an application of the principle of his method to the determination of plagioclases in cleavage-flakes. The following quotation is from the original statement of the method by the above-mentioned writer: [1]

> 'In the microscopical determinations chief reliance was placed upon refractive index measurements made in standardized media. For obtaining *optical dispersion* a graphical method was used as follows. Along the right margin of a cross-section paper refractive indices from 1·520 to 1·870 were written so that readings as close as 0·001 could be made. A line was drawn across the paper through the middle at 45°; along this line the refractive index n_D of each liquid was marked; above and below each such point were placed points, suitably spaced for interpolation, marking the index of the liquid for other wavelengths; points representing a given wavelength were connected.
>
> Two (or more) refractive indices[2] of a salt under investigation were found with the aid of a monochromatic illuminator, and placed on the plot. The dispersion was read from a straight line through these points . . .'

The immersion method, owing to its many advantages over other methods, is now very extensively used in petrology to identify rock constituents. For this purpose the refractive indices for sodium-light (n_D) are found. Merwin's graphical method of obtaining the dispersion can be applied to the finding of n_D in the following way. Determine, with the aid of a monochromatic illuminator, two or more refractive indices (for different wave-lengths) of a substance, locate these on the plot, and connect them; then the intersection of the connecting line just drawn with the line representing n_D of the immersion media will give n_D of the

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[1] E. Posnjak and H. E. Merwin, Journ. Amer. Chem. Soc., 1922, vol. 44, p. 1970.

[2] i. e. refractive indices for two or more different wave-lengths.

substance under investigation. P. Eskola[1] has used this method in his petrological work on the contact phenomena between gneiss and limestone in western Massachusetts.

To determine the principal refractive indices of a double-refracting crystal by the above method it is necessary either to have specially orientated pieces, or, if grains of random orientation are used, to repeat the determinations with a large number of grains. For the purpose of identification, however, it is not always necessary to determine the principal refractive indices. In determining plagioclases, for instance, the refractive indices in the cleavage-flakes parallel to $b\,(010)$ or $c\,(001)$ are more conveniently used than α, β, and γ, since these cleavage-flakes are easily obtainable even from such small crystals as are common in rocks.[2] Moreover, the process of finding n_D, in this case, is much simplified by utilizing the known dispersion data of plagioclases, as will be shown later.

Refractive Indices of Plagioclases in Cleavage-flakes.

In 1920 the present writer published a diagram showing the relation between the refractive indices (for sodium-light) in the cleavage-flakes of plagioclases and their chemical compositions.[3]

The diagram on the right half of the accompanying plate (Pl. I) is essentially the same as that published before. But here the calculation of the refractive indices has been entirely repeated and done in detail based on more carefully selected data, some of which were not available at the time of the publication of the previous paper. The result now presented is, therefore, thought to be more correct.

The refractive indices of plagioclases in the cleavage-flakes parallel to $b\,(010)$ and $c\,(001)$ were calculated as follows:

The normal velocities of light, V_1 and V_2 (where $V_1 > V_2$), in a given direction of a crystal are expressed by

$$\left.\begin{aligned} V_1^2 &= \tfrac{1}{2}(v^2+w^2)+\tfrac{1}{2}(v^2-w^2)\cos(\psi-\psi') \\ \text{and}\qquad V_2^2 &= \tfrac{1}{2}(v^2+w^2)+\tfrac{1}{2}(v^2-w^2)\cos(\psi+\psi') \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots(1)$$

where v and w are respectively the greatest and smallest principal velocities, and ψ and ψ' are the angular distances of the direction under consideration from the optic binormals, A and B, on the opposite sides of the optic elasticity axis Z.

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[1] P. Eskola, Journ. Geol. Chicago, 1922, vol. 30, p. 265.

[2] Finely crushed grains of plagioclases are mostly cleavage-flakes.

[3] S. Tsuboi, Journ. Geol. Soc. Tokyo, 1920, vol. 27, p. 392. The diagram was reproduced in A. Johannsen, 'Essentials for the Microscopical Determination of Rock-forming Minerals and Rocks.' Chicago, 1922, folding table.

Let n_1 and n_2 be respectively the refractive indices corresponding to V_1 and V_2. Then from the relations

$$V_1 = \frac{1}{n_1}, \quad V_2 = \frac{1}{n_2}, \quad v = \frac{1}{\alpha}, \quad \text{and} \quad w = \frac{1}{\gamma},$$

(1) may be transformed into

$$\left.\begin{aligned} n_1^2 &= \frac{2\gamma^2\alpha^2}{(\gamma^2+\alpha^2)+(\gamma^2-\alpha^2)\cos(\psi-\psi')} \\ n_2^2 &= \frac{2\gamma^2\alpha^2}{(\gamma^2+\alpha^2)+(\gamma^2-\alpha^2)\cos(\psi+\psi')} \end{aligned}\right\}\cdots\cdots\cdots\cdots(2)$$

The values of ψ and ψ' for the normals to $b\,(010)$ and $c\,(001)$ can be

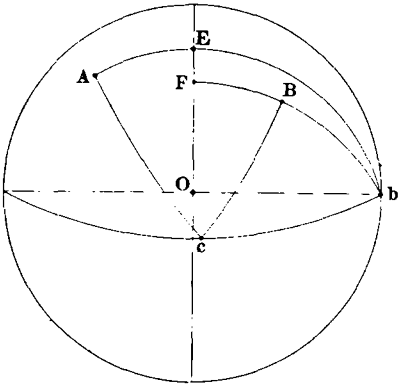

FIG. 1. Stereogram showing the relations between ϕ, λ, ϕ', λ', ψ, and ψ'; projected on the plane perpendicular to the c-axis. $EA = \phi\,(-)$, $OE = \lambda$, $FB = \phi'$, $OF = \lambda'$, $Ab = \psi$ for $b\,(010)$, $Bb = \psi'$ for $b\,(010)$, $Ac = \psi$ for $c\,(001)$, $Bc = \psi'$ for $c\,(001)$.

obtained from those of ϕ, λ, ϕ', and λ' (the meanings of these symbols being the same as in the preceding paper).

For the normal to $b\,(010)$, as is seen in fig. 1,

$$\left.\begin{aligned} \psi &= 90^\circ-\phi \\ \psi' &= 90^\circ-\phi' \end{aligned}\right\}\cdots\cdots\cdots\cdots(3)$$

in the case where the optic elasticity axis Z lies between A and B; or

$$\left.\begin{aligned} \psi &= 180^\circ-(90^\circ-\phi) = 90^\circ+\phi \\ \psi' &= 90^\circ-\phi' \end{aligned}\right\}\cdots\cdots\cdots\cdots(4)$$

in the case where the optic elasticity axis X lies between A and B.

ψ and ψ' for the normal to $c\,(001)$ can be obtained as follows:

In the relations

$$\left.\begin{aligned} \cos cA &= \cos bA \cos bc + \sin bA \sin bc \cos cbA \\ \text{and} \qquad \cos cB &= \cos bB \cos bc + \sin bB \sin bc \cos cbB \end{aligned}\right\}$$

we have
$$\left.\begin{aligned} cbA &= \lambda + \angle\beta - 90^\circ \\ cbB &= \lambda' + \angle\beta - 90^\circ \end{aligned}\right\} \qquad \left.\begin{aligned} bA &= 90^\circ - \phi \\ bB &= 90^\circ - \phi' \end{aligned}\right\}$$

and
$$\left.\begin{aligned} cA &= \psi \\ cB &= \psi' \end{aligned}\right\} \quad \text{or} \quad \left.\begin{aligned} cA &= 180^\circ - \psi \\ cB &= \psi' \end{aligned}\right\}$$

according as Z or X lies between A and B.

Therefore

$$\left.\begin{aligned} \cos\psi &= \sin\phi\ \cos bc + \cos\phi\ \sin bc \sin(\lambda + \angle\beta) \\ \cos\psi' &= \sin\phi' \cos bc + \cos\phi' \sin bc \sin(\lambda' + \angle\beta) \end{aligned}\right\} \dots\dots\dots\dots (5)$$

if Z lies between A and B; or

$$\left.\begin{aligned} -\cos\psi &= \sin\phi\ \cos bc + \cos\phi\ \sin bc \sin(\lambda + \angle\beta) \\ \cos\psi' &= \sin\phi' \cos bc + \cos\phi' \sin bc \sin(\lambda' + \angle\beta) \end{aligned}\right\} \dots\dots\dots\dots (6)$$

if X lies between A and B.

The data used for calculation are tabulated in Table I. These were selected at appropriate intervals of chemical composition from a number of the data compiled from the literature. In selecting the data the accuracy both of the optical constants and of the chemical composition have been taken into consideration. Good data for bytownite are lacking. The data for Närödal bytownite[1] ($Ab_{25}An_{75}$) have not been adopted because the refractive indices determined approximately with white light appear to be a little too low for those for sodium-light.

TABLE I.

No.	Mol. % of *An.*	α.	γ.	ϕ.	λ.	ϕ'.	λ'.	bc.	$\angle\beta$.
1	1	1·5285	1·5391	−49° 0′	+64° 12′	−47° 12′	−77° 6′	86° 29′	111° 36′
2	13	1·5335	1·5423	−46 30	+66 30	+47 30	+86 30	86 21*	116 30*
3	20	1·5388	1·5463	−42 0	+69 0	+44 0	+70 0	86 18*	116 26*
4	24	1·5403	1·5481	−40 9	+68 2	+42 25	+61 22	86 15	116 24*
5	35	1·5450	1·5525	−41 42	+75 48	+39 42	+42 18	86 13	116 18
6	41	1·5482	1·5556	−42 48	+80 18	+37 54	+35 30	86 10	116 14
7	52	1·5553	1·5632	−55 42	+76 42	+35 0	+15 42	86 6*	116 9*
8	66	1·5623	1·5713	−55 9	+70 16	+26 13	+ 9 55	86 8	116 4
9	95	1·5738	1·5872	−63 0	+56 55	− 2 36	− 6 12	85 52	115 55*

The values of bc and $\angle\beta$ marked with asterisk * in Tables I–XI were taken from E. Schmidt, Die Winkel der kristallographischen Achsen der Plagioklase. Chemie der Erde, Jena, 1915, vol. 1, p. 351; Inaug.-Diss., Heidelberg, 1916. [Min. Abstr., vol. 1, p. 390.]

(1) Albite from Sajóháza, Com. Gömör, Hungary. $Or_{0\cdot5}\,Ab_{99\cdot0}\,An_{0\cdot5}$ ($Ab_{99}\,An_1$ nearly). M. Vendl, Centralblatt Min., 1922, p. 97. [Min. Abstr., vol. 1, p. 391.] G. Melczer, Zeits. Kryst. Min., 1905, vol. 40, p. 581.

(2) Oligoclase-albite from Soboth, Styria. $Ab_{87}\,An_{13}$. F. Becke, Tscherm. Min. Petr. Mitt., 1901, vol. 20, p. 67. The refractive indices in the above table

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[1] F. Becke, Tscherm. Min. Petr. Mitt., 1894, vol. 14, p. 430.

are the mean values of those given in Becke's paper ($\alpha = 1{\cdot}5333$, $\gamma = 1{\cdot}5417$, and $\alpha = 1.5337$, $\gamma = 1.5429$).

(3) Oligoclase. F. Becke, in Doelter's Handbuch der Mineralchemie, 1914, vol. 2, part 1, p. 10. [Based on the data for oligoclase crystals from Ytterby, Sweden (F. Becke, Denkschr. Akad. Wiss. Math.-naturw. Kl. Wien, 1913, vol. 75, p. 142) and from Bakersville, North Carolina (H. Tertsch, Tscherm. Min. Petr. Mitt., 1900, vol. 20, p. 85).]

(4) Oligoclase from Hawke mine, Bakersville, North Carolina. $Or_{0\cdot9}\,Ab_{75\cdot1}\,An_{24\cdot0}$ ($Ab_{76}\,An_{24}$ nearly). S. Tsuboi, preceding paper.

(5) Andesine from Hohenstein, Kremsthal, Austria. $Ab_{65}\,An_{35}$. O. Grosspietsch, Sitzungsber. Akad. Wiss. Math.-naturw. Kl. Wien, 1918, Abt. I, vol. 127, p. 439. [Min. Abstr., vol. 1, p. 281.] F. Becke, Tscherm. Min. Petr. Mitt., 1921, vol. 35, p. 33. [Min. Abstr., vol. 2, p. 61.] Different values are given in these two papers. The values in the table are those given in F. Becke's paper.

(6) Andesine from St. Raphael, Esterel, France. $Or_3\,Ab_{57}\,An_{40}$ ($Ab_{59}\,An_{41}$ nearly). F. Becke and M. Goldschlag, Sitzungsber. Akad. Wiss. Math.-naturw. Kl. Wien, 1918, Abt. I, vol. 127, p. 502. [Min. Abstr., vol. 1, p. 391.]

(7) Labradorite. F. Becke, same as (3). [Based on the data for labradorite crystals from St. Paul's Island (Rosenbusch-Wülfing, Mikroskopische Physiographie, 1905, vol. 1, part 2, pl. 8) and from Labrador (W. Luczizky, Tscherm. Min. Petr. Mitt., 1906, vol. 24, p. 191).]

(8) Labradorite from St. John's Point, County Down, Ireland. $Or_{5\cdot0}\,Ab_{32\cdot7}\,An_{62\cdot3}$ ($Ab_{34}\,An_{66}$ nearly). S. Tsuboi, preceding paper.

(9) Anorthite from Miyakejima, Idzu, Japan. $Ab_{3\cdot9}\,An_{95\cdot4}\,Cg_{0\cdot7}$ ($Ab_5\,An_{95}$ nearly). S. Kôzu, Sci. Rep. Tôhoku Imp. Univ. Sendai, Japan, 1914, ser. 2, vol. 2, p. 7. Y. Kikuchi, Journ. Coll. Sci. Imp. Univ. Japan, 1888, vol. 2, part 1, p. 31.

From the data in Table I the refractive indices in the cleavage-flakes were calculated by the relations already given. For albite (no. 1 in the table) the formulae (3) and (5) were applied, and for the remaining felspars the formulae (4) and (6). The results of the calculation are shown in Table II. The diagram on the right half of the accompanying plate is based on the data in Table II.

TABLE II.—Refractive Indices for Sodium-light in the Cleavage-flakes of Plagioclases.

No.	Mol. % of *An*.	*b* (010)		*c* (001)	
		n_1.	n_2.	n_1.	n_2.
1	1	1·5285	1·5332	1·5290	1·5388
2	13	1·5335	1·5376	1·5337	1·5423
3	20	1·5388	1·5428	1·5388	1·5463
4	24	1·5403	1·5447	1·5403	1·5480
5	35	1·5450	1·5493	1·5450	1·5520
6	41	1·5482	1·5525	1·5482	1·5548
7	52	1·5555	1·5592	1·5560	1·5617
8	66	1·5628	1·5674	1·5634	1·5693
9	95	1·5777	1·5838	1·5780	1·5828

Dispersion of Refractive Indices in Cleavage-flakes.

The refractive indices of plagioclases in cleavage-flakes parallel to *b* (010) and *c* (001) for the light of various wave-lengths were calculated in the same way as above from the dispersion data[1] in Tables III–XI.

TABLE III.—Albite from Rischuna, Switzerland. $Or_{1\cdot 9}\,Ab_{97\cdot 7}\,An_{0\cdot 4}$. (S. Kôzu, Min. Mag., 1915, vol. 17, p. 189. Berta Krebs, Zeits. Krist., 1921, vol. 56, p. 388. [Min. Abstr., vol. 1, p. 281.])

The optical orientation of this felspar is not known. The figures given under ϕ, λ, ϕ', and λ' in the table are those for albite from Sajóháza, Com. Gömör, Hungary, with which the Rischuna albite is very similar in refractive indices (cf. no. 1 in Table I).

Wave-lengths (in $\mu\mu$).	α.	γ.	ϕ.	λ.	ϕ'.	λ'.
700	1·5254	1·5354				
671	1·5260	1·5360				
644	1·5268	1·5370				
610	1·5283	1·5385				
589·3	1·5289	1·5392	−49° 0′	+64° 12′	−47° 12′	−77° 6′
554	1·5305	1·5408				
535	1·5315	1·5419				
527	1·5321	1·5424				
508·5	1·5331	1.5435				
486	1·5347	1·5455				

bc (for Gömör albite) = 86° 29′. $\angle\beta$ (for Gömör albite) = 116° 36′.

TABLE IV.—Albite from Lakous, Island of Crete. $Ab_{99.1}\,Or_{0\cdot 9}$. (C. Viola, Tscherm. Min. Petr. Mitt., 1895, vol. 15, p. 135; Zeits. Kryst. Min., 1899, vol. 30, p. 437. O. Grosspietsch, Tscherm. Min. Petr. Mitt., 1908, vol. 27, p. 373.)

Wave-lengths (in $\mu\mu$).	α.	γ.	ϕ.	λ.	ϕ'.	λ'.
687	1·5251	1·5347				
656·3	1·5265	1·5361				
589·3	1·5290	1·5386	−43° 30′	+77° 0′	−47° 30′	−77° 30′
527	1·5321	1·5416				
486·1	1.5355	1·5455				

bc = 86° 19′. $\angle\beta$ = 116° 32′.

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[1] The dispersion data for the albite-oligoclase from Bakersville determined by C. Viola (Zeits. Kryst. Min., 1900, vol. 32, p. 336) have not been adopted because they contained conflicting data. The value of n_2 should be greater than that of β (S. Tsuboi, Journ. Geol. Soc. Tokyo, 1918, vol. 25, p. 39; Journ. Coll. Sci. Imp. Univ. Tokyo, 1920, vol. 43, art. 6, p. 63), while n_2 for *b* (010) obtained from Viola's data is less than β.

TABLE V.—Albite from Amelia County, Virginia. $Ab_{97\cdot5}\,An_{2\cdot5}$. (C. Viola, Zeits. Kryst. Min., 1900, vol. 32, p. 318.)

Wave-lengths (in $\mu\mu$).	α.	γ.	φ.	λ.	φ'.	λ'.
687	1·5261	1·5364				
656·3	1·5269	1.5367				
589·3	1·5292	1·5393	−41° 30′	+59° 30′	−47° 0′	−60° 0′
527	1·5325	1·5425				
486·1	1·5350	1.5452				

$bc = 86° 30'$. $\angle\beta = 116° 37'$.*

TABLE VI.—Albite from Kramkogl, Rauris, Salzburg. $Or_{1\cdot8}\,Ab_{94\cdot9}\,An_{3\cdot3}$. (C. Viola, 1900, loc. cit., p. 328.)

Wave-lengths (in $\mu\mu$).	α.	γ.	φ.	λ.	φ'.	λ'.
687	1·5267	1·5356				
656·3	1·5274	1·5363				
589·3	1·5293	1·5390	−40° 0′	+64° 0′	−47° 0′	−81° 0′
527	1·5326	1·5416				
486·1	1·5351	1·5452				

$bc = 86° 15'$. $\angle\beta = 116° 36'$.*

TABLE VII.—Albite from Wallhornthörl, near Prägraten, Tyrol. $Or_{1\cdot1}\,Ab_{95\cdot3}\,An_{3\cdot6}$. (C. Viola, 1900, loc. cit., p. 323. E. Weinschenk, Zeits. Kryst. Min., 1896, vol. 26, p. 501. O. Grosspietsch, 1908, loc. cit., p. 371.) $\angle\beta$ was calculated by the present writer from the data in Viola's paper.

Wave-lengths (in $\mu\mu$).	α.	γ.	φ.	λ.	φ'.	λ'.
687	1·5265	1·5371				
656·3	1·5275	1·5377				
589·3	1·5300	1·5401	−45° 30′	+57° 30′	−52° 0′	−80° 30′
527	1·5334	1·5434				
486·1	1·5361	1·5462				

$bc = 84° 26'$. $\angle\beta = 117° 39'$.

TABLE VIII.—Oligoclase from Hawke mine, Bakersville, North Carolina. $Or_{0\cdot9}\,Ab_{75\cdot1}\,An_{24\cdot0}$. (S. Tsuboi, preceding paper.)

Wave-lengths (in $\mu\mu$).	α.	γ.	φ.	λ.	φ'.	λ'.
700	1·5366	1·5442	−40° 39′	+68° 19′	+42° 33′	+61° 1′
671	1·5373	1·5450	—	—	—	—
644	1·5383	1·5460	−40 25	+68 12	+42 29	+61 11
610	1·5395	1·5472	—	—	—	—
589·3	1·5403	1·5481	−40 9	+68 2	+42 25	+61 22
554	1·5421	1·5497	—	—	—	—
535	1·5431	1·5508	−39 54	+67 51	+42 18	+61 38
527	1·5437	1·5513	—	—	—	—
508·5	1·5450	1·5525	−39 47	+67 43	+42 13	+61 44

$bc = 86° 15'$. $\angle\beta = 116° 24'$.*

TABLE IX.—Labradorite from St. John's Point, County Down, Ireland. $Or_{5\cdot0}\,Ab_{32\cdot7}\,An_{62\cdot3}$. (S. Tsuboi, preceding paper.)

Wave-lengths (in $\mu\mu$).	α.	γ.	ϕ	λ.	ϕ'.	λ'.
700	1·5577	1·5668	−54° 16′	+69° 35′	+25° 33′	+11° 2′
671	1·5587	1·5679	—	—	—	—
644	1·5596	1·5686	−54 37	+69 56	+25 44	+10 29
610	1·5614	1·5703	—	—	—	—
589·3	1·5623	1·5713	−55 9	+70 16	+26 13	+9 55
554	1·5640	1·5731	—	—	—	—
535	1·5652	1·5742	−55 43	+70 86	+26 21	+9 20
527	1·5657	1·5748	—	—	—	—
508·5	1·5671	1·5761	−56 0	+70 47	+26 34	+9 4

bc = 86° 8′. ∠ β = 116° 4′.

TABLE X.[1]—Anorthite from Tarumae, Hokkaidô, Japan. $Or_{0\cdot6}\,Ab_{4\cdot7}\,An_{92\cdot6}\,Cg_{2\cdot0}$. (S. Kôzu, 1914, loc. cit.)

Wave-lengths (in $\mu\mu$).	α.	γ.	ϕ.	λ.	ϕ'	λ'
686	1·5705	1·5835	—	—	—	—
671	1·5709	1·5839	−63° 15′	+58° 38′	−2° 41′	−6° 16′
589·3	1·5736	1·5872	−63 22	+58 44	−2 36	−6 12
535	1·5768	1·5905	−63 26	+58 50	−2 30	−6 11
486	1·5810	1·5947	−63 33	+58 57	−2 27	−6 9

bc = 85° 50′.* ∠ β = 115° 55′.*

TABLE XI.[1]—Anorthite from Miyakejima, Idzu, Japan. $Ab_{3\cdot9}\,An_{95\cdot4}\,Cg_{0\cdot7}$. (S. Kôzu, 1914, loc. cit. Y. Kikuchi, loc. cit.)

Wave-lengths (in $\mu\mu$).	α.	γ.	ϕ.	λ.	ϕ'.	λ'.
686	1·5697	1·5828	—	—	—	—
671	1·5702	1·5834	−62° 36′	+56° 47′	−2° 54′	−6° 5′
589·3	1·5738	1·5872	−63 0	+56 55	−2 36	−6 12
535	1·5770	1·5906	−63 22	+57 2	−2 19	−6 19
486	1·5807	1·5947	−63 50	+57 12	−2 0	−6 26

bc = 85° 52′. ∠ β = 115° 55′.*

To calculate the dispersion of the refractive indices in the cleavage-flakes from the above, certain approximations were necessary owing to the incompleteness of the dispersion data of the optic axes. In the albite (Tables III–VII) the values of ϕ, λ, ϕ', and λ' for sodium-light were used for all the different wave-lengths. In the oligoclase (Table VIII) and the labradorite (Table IX), the values of ϕ, λ, ϕ', and λ' for 644,

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[1] S. Kôzu determined the relative dispersion of the optic axes of these anorthites (Tables X–XI) and calculated ϕ, λ, ϕ', and λ' assuming that the orientation of the optic axis B for sodium-light is the same as that in the anorthite from Vesuvius. (F. Becke, Sitzungsber. Akad. Wiss. Math.-naturw. Kl. Wien, 1899, Abt. I, vol. 108, p. 437.)

589·3, and 535 $\mu\mu$ were used respectively for 671, 610, and 554–527 $\mu\mu$; and in the anorthite (Tables X–XI) those for 671 $\mu\mu$ for 686 $\mu\mu$.

The errors introduced by such approximations, however, are thought to be very small, judging from the qualitative data of the dispersion of the optic axes in felspars. To get an idea of the magnitude of the errors, the refractive indices in the cleavage-flakes of oligoclase and labradorite (Tables VIII–IX) for 700, 644, 535, and 508·5 $\mu\mu$ and those of anorthite (Tables X–XI) for 671, 535, and 486 $\mu\mu$ were calculated using the values of ϕ, λ, ϕ', λ' for 589·3 $\mu\mu$, and compared with those obtained by using the proper values for them; but there has never occurred a difference greater than 0·0001, which is quite negligible for the present purpose.

The dispersion of the refractive indices in the cleavage-flakes as obtained by calculation is shown in Tables XII–XX.

TABLE XII.—Albite from Rischuna, Switzerland. (Cf. Table III.)

Wave-lengths (in $\mu\mu$).	b (010).		c (001).	
	n_1.	n_2.	n_1.	n_2.
700	1·5254	1·5298	1·5259	1·5351
671	1·5260	1·5304	1·5265	1·5357
644	1·5268	1·5313	1·5273	1·5367
610	1·5283	1·5328	1·5288	1·5382
589·3	1·5289	1·5335	1·5294	1·5389
554	1·5305	1·5351	1·5310	1·5405
535	1·5315	1·5361	1·5320	1·5416
527	1·5321	1·5367	1·5326	1·5421
508·5	1·5331	1·5377	1·5336	1·5432
486	1·5347	1·5395	1·5352	1·5452

TABLE XIII.—Albite from Lakous, Island of Crete. (Cf. Table IV.)

Wave-lengths (in $\mu\mu$).	b (010).		c (001).	
	n_1.	n_2.	n_1.	n_2.
687	1·5251	1·5298	1·5258	1·5346
656·3	1·5265	1·5312	1·5273	1·5360
589·3	1·5290	1·5337	1·5298	1·5385
527	1·5321	1·5367	1·5329	1·5415
486·1	1·5355	1·5404	1·5363	1·5454

TABLE XIV.—Albite from Amelia County, Virginia. (Cf. Table V.)

Wave-lengths (in $\mu\mu$).	b (010).		c (001).	
	n_1.	n_2.	n_1.	n_2.
687	1·5261	1·5313	1·5268	1·5356
656·3	1·5269	1·5319	1·5276	1·5360
589·3	1·5292	1·5344	1·5299	1·5385
527	1·5325	1·5376	1·5332	1·5417
486·1	1·5350	1·5402	1·5357	1·5444

TABLE XV.—Albite from Kramkogl, Rauris, Salzburg. (Cf. Table VI.)

Wave-lengths (in $\mu\mu$).	b (010).		c (001).	
	n_1.	n_2.	n_1.	n_2.
687	1·5267	1·5314	1·5270	1·5354
656·3	1·5274	1·5321	1·5277	1·5361
589·3	1·5293	1·5344	1·5297	1·5388
527	1·5326	1·5373	1·5330	1·5414
486·1	1·5352	1·5405	1·5355	1·5450

TABLE XVI.—Albite from Wallhornthörl, near Prägraten, Tyrol. (Cf. Table VII.)

Wave-lengths (in $\mu\mu$).	b (010).		c (001).	
	n_1.	n_2.	n_1.	n_2.
687	1·5265	1·5311	1·5268	1·5369
656·3	1·5275	1·5319	1·5277	1·5375
589·3	1·5300	1·5344	1·5302	1·5399
527	1·5334	1·5377	1·5337	1·5432
486·1	1·5361	1·5405	1·5363	1·5460

TABLE XVII.—Oligoclase from Hawke mine, Bakersville, North Carolina. (Cf. Table VIII.)

Wave-lengths (in $\mu\mu$).	b (010).		c (001).	
	n_1.	n_2.	n_1.	n_2.
700	1·5366	1·5408	1·5366	1·5441
671	1·5373	1·5416	1·5373	1·5449
644	1·5383	1·5426	1·5383	1·5459
610	1·5395	1·5438	1·5395	1·5471
589·3	1·5403	1·5447	1·5403	1·5480
554	1·5421	1·5464	1·5421	1·5497
535	1·5431	1·5475	1·5431	1·5508
527	1·5437	1·5480	1·5437	1·5512
508·5	1·5450	1·5493	1·5450	1·5525

TABLE XVIII.—Labradorite from St. John's Point, County Down, Ireland. (Cf. Table IX.)

Wave lengths (in $\mu\mu$).	b (010).		c (001).	
	n_1.	n_2.	n_1.	n_2.
700	1·5583	1·5630	1·5588	1·5648
671	1·5593	1·5640	1·5599	1·5659
644	1·5601	1·5648	1·5607	1·5666
610	1·5619	1·5665	1·5625	1·5683
589·3	1·5628	1·5674	1·5634	1·5693
554	1·5646	1·5692	1·5652	1·5711
535	1·5658	1·5703	1·5664	1·5722
527	1·5663	1·5709	1·5669	1·5728
508·5	1·5677	1·5722	1·5683	1·5741

Table XIX.—Anorthite from Tarumae, Hokkaidô, Japan. (Cf. Table X.)

Wave-lengths (in $\mu\mu$).	b (010).		c (001).	
	n_1.	n_2.	n_1.	n_2.
686	1·5743	1·5802	1·5745	1·5793
671	1·5747	1·5806	1·5749	1·5796
589·3	1·5776	1·5837	1·5778	1·5826
535	1·5808	1·5869	1·5810	1·5859
486	1·5850	1·5911	1·5852	1·5901

Table XX.—Anorthite from Miyakejima, Idzu, Japan. (Cf. Table XI.)

Wave-lengths (in $\mu\mu$).	b (010).		c (001).	
	n_1.	n_2.	n_1.	n_2.
686	1·5735	1·5795	1·5738	1·5786
671	1·5740	1·5801	1·5743	1·5791
589·3	1.5777	1·5838	1·5780	1·5828
535	1·5810	1·5871	1·5813	1·5861
486	1·5848	1·5910	1·5851	1·5900

To compare the dispersion of the refractive indices in the cleavage-flakes of different felspars, the values[1] of $(n_1-n_{1D})_b$, $(n_1-n_{1D})_c$, $(n_2-n_{2D})_b$, and $(n_2-n_{2D})_c$ were calculated, and are tabulated below (Tables XXI–XXIII).[2] Those in the brackets are interpolated values obtained by drawing the dispersion curves.

Table XXI.—$(n_{1D}-n_1)_b\times10^4$ and $(n_1-n_{1D})_c\times10^4$.

Wave-lengths (in $\mu\mu$).	Albite.	Oligoclase.	Labradorite.	Anorthite.
700	(−34)	−37	−45	(−41)
687 (686)	−30·5 ± 4·5	—	—	−37·5 ± 4·5
671	(−27)	−30	−35	−33 ± 4
656·3	−22 ± 3	—	—	(−29)
644	(−19)	−20	−27	(−25)
610	(− 8)	− 8	− 9	(−10)
n_1 in b and c for 589·3$\mu\mu$.	1·530	1·540	1·563	1·578
554	(+17)	+18	+18	(+20)
535	(+28)	+28	+30	+32·5 ± 0·5
527	+33 ± 2	+34	+35	(+38)
508·5	(+45)	+47	+49	(+52)
486	+61·5 ± 3·5	—	—	+72·5 ± 1·5

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[1] By $(n_1-n_{1D})_b$, &c., are meant the difference between n_1 for the light of a given wave-length and n_1 for sodium-light in b (010), &c.

[2] The refractive indices for 687 $\mu\mu$ of the albite from the Island of Crete (Table XIII) were omitted because they are evidently too low, as can be found by drawing the dispersion curves for this felspar.

TABLE XXII. $(n_2 - n_{2\,D})_b \times 10^4$.

Wave-lengths (in $\mu\mu$).	Albite.	Oligoclase.	Labradorite.	Anorthite.
700	(−34)	−39	−44	(−42)
687 (686)	−31·5 ± 1·5	—	—	−39 ± 4
671	(−28)	−31	−34	−34 ± 3
656·3	−24 ± 1	—	—	(−29)
644	(−20)	−21	−26	(−25)
610	(− 8)	− 9	− 9	(−10)
n_2 in *b* for 589·3 $\mu\mu$.	1·534	1·545	1·567	1·584
554	(+17)	+17	+18	(+20)
535	(+27)	+28	+29	+32·5 ± 0·5
527	+31 ± 2	+33	+35	(+38)
508·5	(+44)	+46	+48	(+52)
486	+62·5 ± 4·5	—	—	+73 ± 1

TABLE XXIII. $(n_2 - n_{2D})_c \times 10^4$.

Wave-lengths (in $\mu\mu$).	Albite.	Oligoclase.	Labradorite.	Anorthite.
700	(−34)	−37	−45	(−41)
687 (686)	−31·5 ± 2·5	—	—	−37·5 ± 4·5
671	(−29)	−30	−34	−33·5 ± 3·5
656·3	−25·5 ± 1·5	—	—	(−29)
644	(−20)	−20	−27	(−25)
610	(− 8)	− 8	−10	(−10)
n_2 in *c* for 589·3 $\mu\mu$.	1·539	1·548	1·569	1·583
554	(+16)	+18	+18	(+21)
535	(+26)	+28	+29	+33 ± 0
527	+29·5 ± 2·5	+34	+35	(+39)
508.5	(+44)	+47	+48	(+53)
486	+64 ± 5	—	—	+73·5 ± 1·5

So far as can be judged from the tables above, the dispersion of the refractive indices in the cleavage-flakes of plagioclases tends to increase as their composition becomes more basic. Based on the data in Tables XXI–XXIII, a series of curves on the left half of the accompanying plate (Pl. I) were drawn by interpolation, from $n_D = 1·529$ to $n_D = 1·583$ with the interval of 0·003 of n_D. The curves belonging to three different felspars pass through the same value of n_D; for instance, the curves for n_1 (in both *b* and *c*) of $Ab_{56}\,An_{44}$, for n_2 in *b* of $Ab_{69}\,An_{31}$, and for n_2 in *c* of $Ab_{71}\,An_{29}$ pass through the point $n_D = 1·550$. As these curves coincide with one another within the limit of errors in constructing the diagram, they can be represented by only one curve.[1]

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[1] The maximum deviation of any of the interpolated central values for n_1 and n_2 (both in *b* and *c*) from the corresponding point on the curve in the diagram is ±0·0002.

Method of Determining Plagioclases.

The diagram on Pl. I, constructed as above stated, affords a means of determining plagioclases in cleavage-flakes. The following example will suffice to demonstrate the method.

Fine cleavage-flakes parallel to $c(001)$ of a certain plagioclase were immersed in a medium whose dispersion is represented by DAE[1] in fig. 2, and placed under a microscope so that the vibration-direction of the light-wave for n_1 was parallel to that of the polarizer. The refractive indices of the medium and the mineral were compared with the aid of a wave-length monochromator (or spectroscopic monochromatic illuminator), and it was found that matching[2] occurred for light of wave-length 540 $\mu\mu$. Then from the point (A in fig. 2) corresponding to 540 $\mu\mu$ on the curve DAE, draw a curve AB (the dispersion curve for felspar) until it cuts the vertical line for 589·3 $\mu\mu$ at B; draw the horizontal line BC to meet the curve for n_1 in $c(001)$ at C; then from C the felspar can be determined as $Ab_{46}An_{54}$.

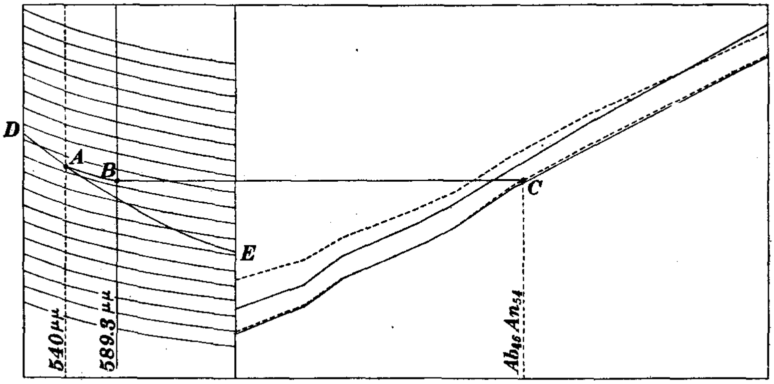

FIG. 2. A sketch of the diagram in the accompanying plate to illustrate the method.

It is not necessary to know whether the immersed cleavage-flakes are parallel to b or c. If it is not known, observe n_1 and find the intersection of BC with the imaginary curve passing through the middle

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[1] A mixture of cassia oil and clove oil, roughly 1 : 2 in volume, had the dispersion represented by DAE.

[2] Under favourable conditions differences less than 0·0002 in refractive indices between liquid and mineral can be detected. (Cf. Merwin, loc. cit.)

points between the curves for n_1 in *b* and *c*. Since the latter two curves are very close (in part coincident), a difference greater than 0·5 % in the molecular percentages of *Ab* and *An* does not occur between the result thus obtained and that determined with pieces of known orientation.

As to the immersion media to be used for this method, those which possess strong dispersion, in addition to the qualities of stability, freedom from colour, &c.,[1] are to be preferred. Cassia oil and clove oil being rather strong in dispersion as shown in the following table, the mixtures of these two are suitable for the present purpose.

TABLE XXIV.—Dispersion of Cassia Oil and Clove Oil (Commercial Material obtained at a Chemist's Shop in Cambridge) at 17° C.

Wave-lengths (in $\mu\mu$).	Cassia oil.	Clove oil.	Wave-lengths (in $\mu\mu$).	Cassia oil.	Clove oil.
700	1·5891	1·5258	554	1·6093	1·5355
671	1.5918	1·5269	535	1·6134	1·5386
644	1·5950	1·5284	527	1·6153	1·5394
610	1·5997	1·5315	508·5	1·6200	1·5416
589·3	1·6029	1·5332			

The method of determining plagioclases described above is very widely applicable since the cleavage-flakes of felspar can be easily obtained, even from such small crystals as occur in rocks. Felspar splinters in the rock powder produced by pounding (not by grinding) a piece of rock in a mortar are mostly cleavage-flakes. In the present method a monochromatic illuminator is necessary and the dispersion of the immersion media must be previously determined;[2] but if this has been once done, then the determination of plagioclases can be made more quickly and at the same time more exactly than by the ordinary immersion method. In the ordinary immersion method a large number of standard media are necessary, while in the present method a few are sufficient for the

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[1] E. S. Larsen, Bull. U.S. Geol. Survey, 1921, no. 679, p. 14.

[2] It is not necessary to determine the dispersion of every immersion medium. If the dispersion of cassia oil and clove oil is determined, the dispersion of any mixture of these two oils can be found graphically as follows :—Along the right and left margins of a cross-section paper, mark the refractive indices for light of various wave-lengths of cassia and clove oils respectively, and connect the points representing a given wave-length. Determine n_D of a certain mixture of these two oils; mark it on the connecting line for sodium-light; and draw a vertical line through n_D. Then the dispersion of the mixture can be read from the intersections of this vertical line with the connecting lines for different wave-lengths.

determination of the whole of the felspars in the plagioclase series, felspars of a rather wide range of chemical composition being determinable with a single medium. In this respect the present method is specially suitable for the study of zoned felspars. With these advantages it is hoped that the method here described may be of use in petrological work.

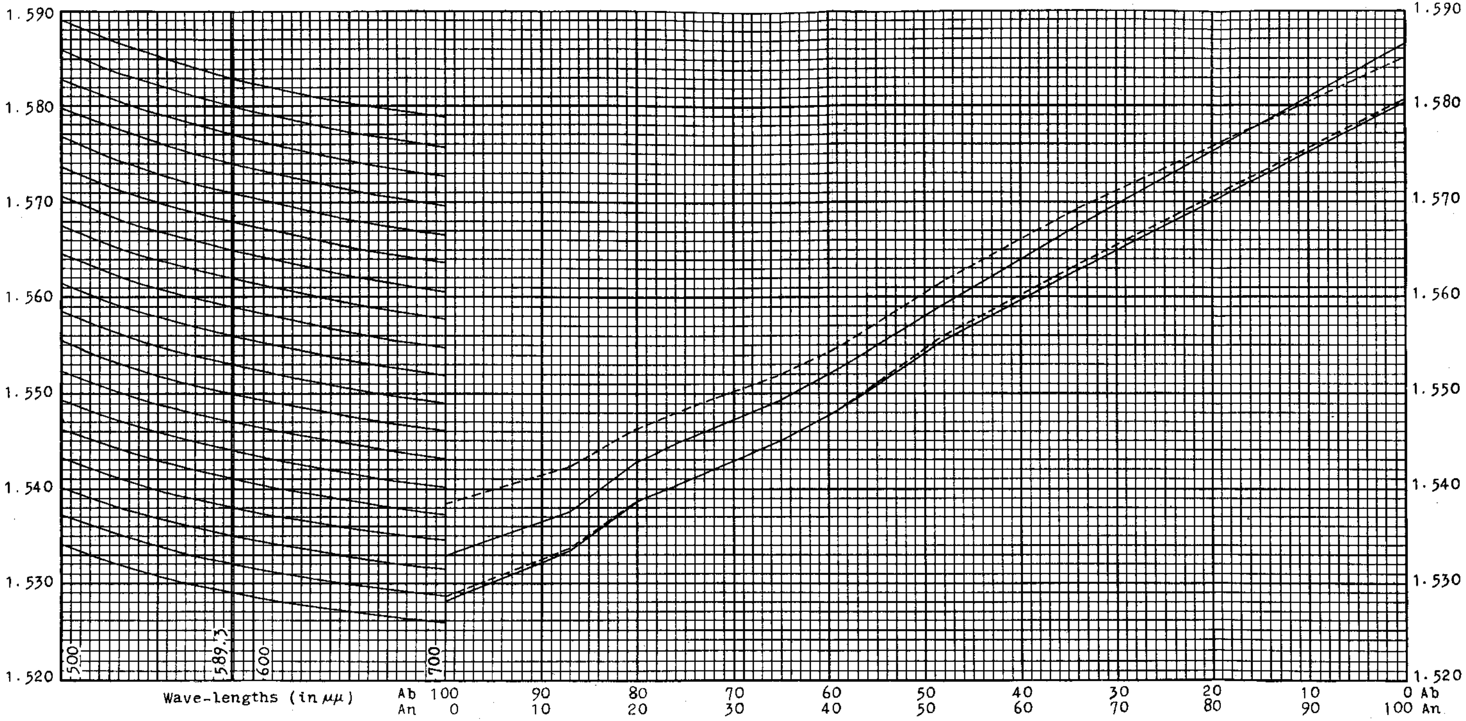
In conclusion, I wish to express my hearty thanks to Prof. W. J. Lewis and Dr. A. Hutchinson, of the University of Cambridge, England, for their kindness in granting me the use of the Mineralogical Laboratory and for constant interest and help throughout the work.

EXPLANATION OF PLATE I.

Diagram for determining plagioclases. (See text-fig. 2, p. 120.)

Right-half: curves of refractive indices in cleavage-flakes parallel to *b* (010) and *c* (001). Broken lines for *c*, solid lines for *b* or both *b* and *c*.

Left-half: curves of dispersion of refractive indices in cleavage-flakes.



SEITARÔ TSUBOI: DIAGRAM FOR DETERMINING PLAGIOCLASES BY THEIR DISPERSION.