THE OPTICAL PROPERTIES OF HEATED PLAGIOCLASES

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ABSTRACT

The optical properties of nine chemically analyzed samples of natural plagioclases have been accurately determined before and after changing them to high-temperature modifications by heat treatment. The change in Nx accompanying the structural change is slight in the composition range An 0 to An 20 and negligible from An 20 to An 100. Ny and Nz change measurably in the composition range An 0 to An 20, but negligibly in the remainder of the composition range. Measurements of principal refractive indices can therefore give a reliable estimate of the composition of a plagioclase regardless of its structural state.

The changes in optic axial angle accompanying the structural changes are such that, given composition, measurements of optic axial angle serve to distinguish low-temperature and high-temperature plagioclases in the composition ranges An 0 to about An 40 and An 60 to about An 90.

INTRODUCTION

Differences between the optical properties of feldspars at low and at high temperatures were reported by Merwin in 1911. Since then, Kohler (1949) has found that the orientation of the optical indicatrix in plagioclases from volcanic rocks is different from that in plagioclases from plutonic rocks. Tuttle and Bowen (1950) were able to distinguish high-temperature and low-temperature modifications of sodic plagioclases by means of optics and x-rays; they found that the low-temperature modifications could be changed to the high by heating at temperatures near those at which melting begins. The x-ray techniques used by Tuttle and Bowen to distinguish between low- and high-temperature plagioclases have been expanded and applied to more extensive groups of samples by Goodyear and Duffin (1954, 1955), J. R. Smith and Yoder (1956), and J. V. Smith (1956). The results of these studies indicate structural differences between low- and high-temperature plagioclases in the composition range An 0 to An 80;† many natural plagioclases are intermediate between the "maximum" low- and high-temperature states so far found. In the composition range An 80 to An 100, Gay (1954) and Laves and Goldsmith (1954) have found structural differences between low- and high-temperature plagioclases by single-crystal x-ray methods. In view of these facts, it is important that carefully controlled tests be made of the differences between the optical properties of low- and high-tempera-

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† Compositions are stated as mole per cent anorthite, calculated as $100(Ca^{++}/Ca^{++}+Na^{+}+K^{+})$.

ture plagioclases throughout the composition range, partly to determine the applicability of presently available refractive index determinative curves to high-temperature plagioclases, and partly to investigate further the optical methods of distinguishing between low- and high-temperature plagioclases. This has been done in the present study by making accurate measurements of the optical properties of chemically analyzed natural plagioclases before and after changing them to the high-temperature forms by heat treatment. This method has the distinct advantage of using the same samples for the measurements in the low- and high-temperature states; observed differences in optical properties cannot therefore be attributed to possible errors in the chemical analyses.

The object of the study was to determine the direction and magnitude of the optical changes in different parts of the composition range rather than to establish accurate determinative curves for maximum high-temperature plagioclases, because such plagioclases appear to be rare in nature, and the curves would be of little practical value.

METHODS

Carefully purified and chemically analyzed samples of natural plagioclases ranging in composition from pure albite to almost pure anorthite were available at the Geophysical Laboratory, thanks to many contributors; the samples selected for study are listed and described in Table 1. The optical properties of most of these samples had previously been measured by the writer using techniques developed in cooperation with H. H. Hess. These techniques are described in detail in a memoir of the Geological Society of America (Smith, in Hess, in press). Briefly, total birefringence was determined on the universal stage by accurate comparison with the total birefringence of quartz, which is known to the fifth decimal place. Optic axial angles (2V) were measured by the standard orthoscopic procedure (Fairbairn and Podolsky, 1951) in thin sections of grains mounted in bakelite. Refractive indices were determined by a controlled-temperature universal stage technique, in which a grain, illuminated in sodium light, is rotated from a principal orientation toward another principal orientation until the refractive index of the grain exactly matches that of the oil in which it is immersed, at which point it disappears if it is colorless and transparent. Knowing the index of the oil, the angle of rotation from the principal orientation, and the birefrigence of the section of the mineral perpendicular to the axis of rotation, two principal refractive indices of the grain can be calculated. If 2V is also known, the third principal index can be calculated. In determining each of the optical properties, measurements were made on several different grains in each sample and averaged. The estimated accuracy

of the average values of refractive indices is ± 0.0003, of total bire-fringence ± 0.0001, and of 2V $\pm 0.5°$. The optical properties of the plagioclase samples selected for study were measured by these methods

TABLE 1. DESCRIPTION OF PLAGIOCLASE SAMPLES

Sample No.	Composition (mole %)			Analyst	Occurrence and Locality	Contributor
	An	Ab	Or			
D761-1	0.2	98.7	1.1	R. E. Stevens*	Pegmatite, Ramona, Calif.	C. S. Ross
D761-3	0.4	98.2	1.4	R. E. Stevens*	Pegmatite, Amelia, Va.	C. S. Ross
80165	21.6	74.5	3.9	E. Chadbourn**	Pegmatite, Hawk Mine, Bakersville, N. C.	F. C. Kracek
D638	29.8	69.7	0.5	R. E. Stevens*	Pegmatitic vein in dunite, Macon Co., N.C.	C. S. Ross
1963	44.2	53.7	2.1	E. H. Oslund*	Ferrogabbro, Skaergaard Intrusion, East Greenland.	L. R. Wager
GD29	51.8	46.3	1.9	E. H. Oslund*	Dolerite, Great Dyke, S. Rhodesia.	H. H. Hess
BV63	59.2	38.6	2.2	E. H. Oslund*	Gabbro, Bushveld Igneous Complex, South Africa.	H. H. Hess
EB41	62.5	36.8	0.7	E. H. Oslund*	Gabbro, Stillwater Igneous Complex, Montana.	H. H. Hess
EB38	80.0	19.5	0.5	A. H. Phillips*	Norite, Stillwater Igneous Complex, Montana.	H. H. Hess
Synthetic anorthite	100	0	0	—	Crystallized from anhydrous glass at 1500° C. and cooled very quickly to room temperature.	J. F. Schairer

* Analysis quoted in Smith (in Hess, in press).
** Analysis quoted in Kracek and Neuvonen (1952).

before and after changing them to high-temperature modifications by heat treatment. The samples (100- to 200-mesh in grain size) were heated in platinum crucibles in platinum-wound electric resistance furnaces; temperatures were measured with Pt-Pt10Rh thermocouples, and were controlled and recorded continuously, the recorded variations being less than $\pm 5°$ C. The progress of the structural changes was checked by removing the samples from the furnaces at intervals and measuring $2\theta(131)-2\theta(1\bar{3}1)$ in x-ray powder diffraction patterns, using the same techniques and instruments as those described by J. R. Smith and Yoder (1956). Many grains in some of the samples heated in this way were found to contain blebs and sheets of glass, even though the maximum temperatures at which they were heated were somewhat lower than the temperatures of beginning of melting for the compositions concerned (see Table 2 and Bowen, 1913). This was undoubtedly a result of the lowering of the melting temperature by foreign inclusions in the grains of plagioclase. Four samples in the composition range An 0 to An 30, which contain very few inclusions, contained very little glass after heating. Five samples in the composition range An 44 to An 80, which contain rather abundant solid inclusions, contained enough blebs of glass after heating to make the material unsuitable for refractive index determinations. In order to obtain material in the high-temperature form suitable for refractive index measurements, six samples were held for one week at $990° \pm 5°$ C. in water at a pressure of 1000 psi. This was done in cold-seal type pressure vessels (Tuttle, 1949), the samples being contained in small unsealed platinum tubes. Some grains in the samples subjected to this hydrothermal treatment were found to contain blebs of glass, but not in sufficient amount to hinder refractive index measurements; many grains contained no visible glass.

Discussion of Results

1. *Structural state of samples*

The values of $2\theta(131)-2\theta(1\bar{3}1)$ before and after heating the samples are listed in Table 2; the initial and final values are plotted in Fig. 1. The curve in Fig. 1 represents $2\theta(131)-2\theta(1\bar{3}1)$ for plagioclases synthesized in the dry way, and is taken from J. R. Smith and Yoder (1956). These plagioclases are probably the highest temperature modifications which can exist metastably at room temperature, because they were crystallized at temperatures near those at which melting begins in the anhydrous binary system $NaAlSi_3O_8$-$CaAl_2Si_2O_8$, and were quenched quickly to room temperature. The curve in Fig. 1 therefore represents *maximum* high-temperature plagioclases. The values of $2\theta(131)-2\theta(1\bar{3}1)$

TABLE 2. HEAT TREATMENT AND X-RAY MEASUREMENTS

Sample No.	Heat Treatment*	$2\theta(131)-2\theta(1\bar{3}1)$** (CuK$\alpha$)
D761-1 (An 0.2)	(1) None (2) $24\frac{1}{2}$ days—1080° C. dry	1.08° 1.98
D761-3 (An 0.4)	(1) None (2) $24\frac{1}{2}$ days—1080° C. dry (H) 1 day—975° C., 3700 psi H_2O	1.09 1.98 1.95
80165 (An 21.6)	(1) None (2) 14 days—1100° C. dry (3) 28 days—1120° C. dry	1.52 1.91 1.92
D638 (An 29.8)	(1) None (2) 14 days—1100° C. dry (3) 28 days—1160° C. dry (H) 7 days—990° C., 1000 psi H_2O	1.74 1.98 1.98 1.94
1963 (An 44.2)	(1) None (2) 7 days—1150° C. dry (3) 4 days—1200° C. dry (4) 28 days—1230° C. dry (H) 7 days—990° C., 1000 psi H_2O	1.79 1.97 1.99 2.00 1.95
GD29 (An 51.8)	(1) None (2) 7 days—1150° C. dry (3) 4 days—1200° C. dry (4) 28 days—1270° C. dry (H) 7 days—990° C., 1000 psi H_2O	1.82 2.00 2.01 2.00 1.99
BV63 (An 59.2)	(1) None (2) 7 days—1150° C. dry (3) 4 days—1200° C. dry (4) 28 days—1310° C. dry (H) 7 days—990° C., 1000 psi H_2O	1.87 2.05 2.04 2.05 2.02
EB41 (An 62.5)	(1) None (2) 8 days—1150° C. dry (3) 14 days—1200° C. dry (4) 28 days—1310° C. dry (H) 7 days—990° C., 1000 psi H_2O	1.91 2.07 2.08 2.05 2.06
ED38 (An 80.0)	(1) None (2) 8 days—1150° C. dry (3) 14 days—1200° C. dry (4) 28 days—1420° C. dry (H) 7 days—990° C., 1000 psi H_2O	2.12 2.18 2.19 2.17 2.19
Synthetic anorthite (An 100)	Crystallized from anhydrous glass at 1500° C., cooled very quickly to room temperature.	2.28

* Numbers in parentheses indicate successive heatings of *same* sample. (H) indicates hydrothermal treatment of a *different* sample.
** Values listed are averages of three or more measurements.
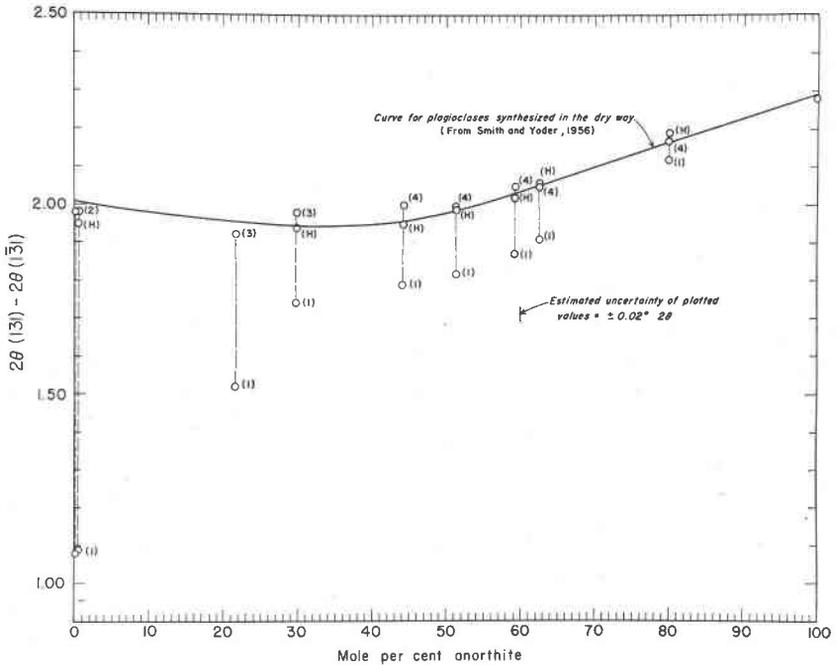
Fig. 1. $2\theta(131)-2\theta(1\bar{3}1)$ for plagioclase samples before and after heating. Numbers and letters in parentheses refer to heat treatment of samples described in Table 2.

plotted in Fig. 1 show that the samples studied optically, whether heated in air or hydrothermally, were changed nearly or quite completely to maximum high-temperature plagioclases. Synthetic anorthite (An 100) was not reheated, but it is assumed to be in the high-temperature form because it was crystallized at 1500° C. and quenched quickly to room temperature. The assumption is supported by the fact that in single-crystal x-ray photographs of grains from this sample, "c"-type reflections are very diffuse and "d"-type reflections are apparently absent (cf. Gay, 1954).

2. Changes in optical properties

The measurements of optical properties before and after heating are listed in Table 3. Except for the values of Ny and Nz, each of the measurements listed was determined on a different grain in the heated or unheated samples. Because of the method of determination, individual determinations of Ny and Nz have the same range of values as do the individual determinations of Nx, so that for convenience only the mean values of Ny and Nz are listed.

TABLE 3. OPTICAL PROPERTIES BEFORE AND AFTER HEATING

NOTE: All measurements before heating except for samples D761-3, 80165, and synthetic anorthite are taken from Smith (in Hess, in press).

Numbers in parentheses and (H) refer to heat treatment of samples described in Table 2.

Sample No.	Nx Before heating	Nx After heating	N_y (Means) Before heating	N_y (Means) After heating	N_z (Means) Before heating	N_z (Means) After heating	N_z-N_x Before heating	N_z-N_x After heating	$2V_z$ Before heating	$2V_z$ After heating
D761-1 (An 0.2)	1.5285	(2)					.01003	(2)	76.4°	(2)
	1.5285	1.5270					.01008	.00839	76.4	129.8°
	1.5286	1.5271					.01018	.00842	77.0	132.4
	1.5286	1.5271		(2)		(2)	.01022	.00846	77.2	133.2
	1.5286	1.5271	1.5326	1.5344	1.5388	1.5357	.01023	———	77.3	133.5
	1.5287	1.5276					.01026	Mean	77.7	133.7
	1.5290	1.5278					.01033	.00842	77.8	133.8
							.01037		78.0	134.3
	Mean	Mean							———	134.4
	1.5286	1.5273					Mean		Mean	———
							.01021		77.2	Mean
										133.1
D761-3 (An 0.4)	1.5286	(2)					.00983	(2)	75.9°	(2)
	1.5286	1.5268		(2)		(2)	.00989	.00840	76.3	133.8°
	1.5286	1.5269	1.5326	1.5343	1.5387	1.5356	.00989	.00848	76.5	134.2
	1.5287	1.5273					.00994	.00849	76.6	134.6
	1.5288	1.5274					.01007	.00851	76.7	134.7
	1.5289	———							———	135.3
	1.5294	Mean					Mean	Mean	Mean	135.3
	———	1.5271					.00992	.00847	76.4	———
	Mean									Mean
	1.5288									134.7
		(H)						(H)		
		1.5266						.00845		(H)
		1.5268		(H)		(H)		.00852		132.1°
		1.5268		1.5340		1.5354		.00859		132.3
		1.5269						.00862		133.7
		1.5270						.00869		133.9
		———						———		134.5
		Mean						Mean		———
		1.5268						.00857		Mean
										133.3
80165 (An 21.6)	1.5388	(3)					.00763	(3)	92.8°	(3)
	1.5388	1.5383		(3)		(3)	.00764	.00721	93.0	116.5°
	1.5390	1.5386	1.5431	1.5440	1.5467	1.5459	.00764	.00728	93.4	117.1
	1.5391	1.5387					.00768	.00732	93.6	117.7
	1.5392	1.5389					.00782	.00743	93.9	118.7
	1.5392	———					———	.00745	94.2	119.3
	———	Mean					Mean		———	———
	Mean	1.5386					.00768	Mean	Mean	Mean
	1.5390							.00734	93.5	117.9
D638 (An 29.8)	1.5433	(3)					.00733	(3)	91.4°	(3)
	1.5433	1.5433					.00735	.00723	91.9	104.8°
	1.5433	1.5436		(3)		(3)	.00739	.00732	92.0	105.1
	1.5435	1.5436	1.5479	1.5483	1.5514	1.5510	.00752	.00752	94.0	105.2
	1.5437	1.5437					.00756	.00761	94.4	105.4
	1.5439	1.5438					.00777	———	94.5	105.4
	1.5442	———					.00778	Mean	94.6	———

TABLE 3. (Continued)

Sample No.	Nx Before heating	Nx After heating	Ny (Means) Before heating	Ny (Means) After heating	Nz (Means) Before heating	Nz (Means) After heating	Nz−Nx Before heating	Nz−Nx After heating	2Vz Before heating	2Vz After heating
	1.5444 1.5444 1.5450 — Mean 1.5439	Mean 1.5436 (H) 1.5437 1.5437 1.5438 1.5440 1.5440 Mean 1.5438		(H) 1.5483		(H) 1.5510	—— Mean .00753	.00744 (H) .00714 .00715 .00716 .00716 —— Mean .00715	94.7 94.7 94.8 95.1 — Mean 93.6	Mean 105.2 (H) 103.6° 104.3 104.4 105.2 — Mean 104.4
1963 (An 44.2)	1.5506 1.5506 1.5506 1.5506 1.5517 1.5519 1.5520 1.5520 1.5520 1.5521 1.5525 1.5525 — Mean 1.5516	(H) 1.5520 1.5520 1.5522 1.5523 1.5525 —— Mean 1.5522	1.5547	—	1.5590	(H) 1.5595	.00721 .00722 .00736 .00739 .00750 .00754 .00757 —— Mean .00740	(H) .00719 .00730 .00733 .00736 —— Mean .00730	Variable	Variable
GD29 (An 51.8)	1.5540 1.5541 1.5542 1.5545 1.5548 1.5548 1.5549 1.5550 1.5558 — Mean 1.5547	(H) 1.5539 1.5545 1.5547 1.5549 1.5550 1.5553 —— Mean 1.5547	1.5575	(H) 1.5576	1.5621	(H) 1.5621	.00738 .00740 .00748 .00751 .00752 —— Mean .00746	(4) .00736 .00738 .00753 .00753 —— Mean .00745	75.0° 75.0 75.7 75.7 76.0 76.0 76.3 76.5 76.6 76.6 77.0 77.0 77.7 78.1 78.2 —— Mean 76.4	(4) 76.0° 76.6 76.6 76.7 76.8 78.0 —— Mean 76.8
BV63 (An 59.2)	1.5579 1.5580 1.5581 1.5581 1.5581 1.5583 1.5586 — Mean 1.5582	(H) 1.5577 1.5579 1.5581 1.5586 1.5587 —— Mean 1.5582	1.5615	(H) 1.5611	1.5662	(H) 1.5662	.00776 .00794 .00796 .00813 .00814 .00814 —— Mean .00801	(4) .00792 .00793 .00799 .00806 —— Mean .00797	78.8° 79.0 79.0 79.3 79.4 81.6 — Mean 79.5	(4) 73.0° 73.3 73.6 74.0 74.7 74.8 — Mean 73.9

TABLE 3. (Continued)

Sample No.	Nx Before heating	Nx After heating	Ny (Means) Before heating	Ny (Means) After heating	Nz (Means) Before heating	Nz (Means) After heating	$Nz-Nx$ Before heating	$Nz-Nx$ After heating	$2V_z$ Before heating	$2V_z$ After heating
EB41 (An 62.5)	1.5589 1.5598 1.5599 1.5600 1.5603 1.5604 1.5605 1.5607 1.5607 1.5615 1.5615 — Mean 1.5604	(H) 1.5599 1.5600 1.5602 1.5604 1.5605 1.5611 — Mean 1.5603	(H) 1.5640	(H) 1.5634	(H) 1.5687	(H) 1.5684	.00791 .00812 .00821 .00823 .00823 .00825 .00826 .00830 .00831 .00832 .00837 .00850 .00852 .00853 .00871 — Mean .00832	(4) .00792 .00796 .00817 .00826 .00827 .00834 — Mean .00815	78.5° 79.0 79.7 80.6 81.5 81.8 82.0 82.2 82.2 82.2 82.2 82.6 82.6 82.6 82.7 82.8 82.9 83.1 83.3 83.4 84.5 84.5 — Mean 82.1	(4) 74.8° 75.1 75.5 75.8 76.0 76.3 — Mean 75.6
EB38 (An 80.0)	1.5664 1.5668 1.5668 1.5669 1.5669 1.5669 1.5670 1.5670 1.5671 1.5671 1.5671 1.5672 1.5673 1.5673 1.5673 1.5679 — Mean 1.5671	(H) 1.5667 1.5668 1.5670 1.5671 1.5677 — Mean 1.5671	(H) 1.5729	(H) 1.5716	(H) 1.5778	(H) 1.5765	.01046 .01058 .01061 .01066 .01070 .01076 .01081 .01088 .01090 — Mean .01071	(4) .00888 .00896 .00910 .00955 .00963 .00983 .00993 — Mean .00941	93.7° 93.7 94.2 94.4 94.5 95.1 96.0 96.1 96.2 96.6 — Mean 95.0	(4) 86.1° 87.2 87.7 88.1 88.1 — Mean 87.5
Synthetic anorthite (An 100)	1.5746 1.5748 1.5749 1.5750 1.5752 1.5754 1.5754 — Mean 1.5750		1.5834		1.5883		.01307 .01326 .01328 .01334 .01343 .01352 — Mean .01331		104.2° 104.7 104.8 104.9 105.3 — Mean 104.8	

As stated previously, some of the samples studied were heated in air and some were heated hydrothermally at lower temperatures in order to avoid the formation of glass around inclusions in the grains, which hinders refractive index measurements. Refractive indices of the five samples in the composition range An 44 to An 80 were determined only on material heated hydrothermally. In order to be sure that plagioclase heated hydrothermally has the same optical properties as that heated in air, two samples, D761-3 (An 0.4) and D638 (An 29.8), were changed to
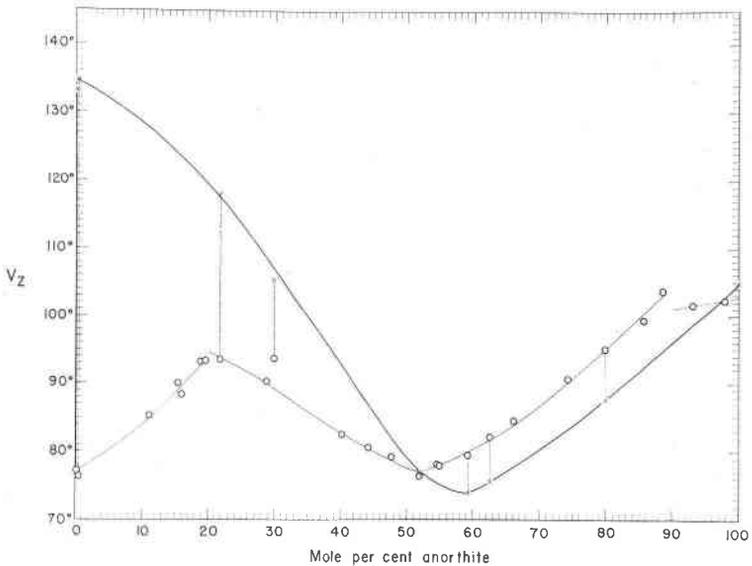
Fig. 2. Optic axial angle of plagioclase samples before (open circles) and after (crosses) heating. Light curve is for low-temperature plagioclases, taken from Smith (in Hess, in press). Heavy curve is tentative curve for maximum high-temperature plagioclases.

the high-temperature forms in both ways, and the optical properties of both products were measured. The measurements are listed in Table 3, and they show that no significant differences in any of the optical properties result from the difference in the method of heating.

The average values of $2V_z$ before and after heating are plotted in Fig. 2. In this figure the curve for low-temperature plagioclases (light-line curve) is essentially the same as that in Smith (in Hess, in press), with a few additional determinations which are listed in an appendix to the present paper. All the samples on which it is based have been studied by x-ray methods (J. R. Smith and Yoder, 1956, and unpublished single-crystal studies); by comparison with other natural plagioclases, they are

known to be the lowest temperature plagioclases so far found. The changes in $2V_z$ caused by heating suggest that the curve for maximum high-temperature plagioclases has the shape of the heavy line in Fig. 2. From this it may be seen that, knowing composition, high-temperature and low-temperature plagioclases in the composition ranges An 0 to about An 40 and An 60 to about An 90 can be distinguished by accurate 2V measurements. Relations in the range An 90 to An 100 remain somewhat ambiguous, and require further study.
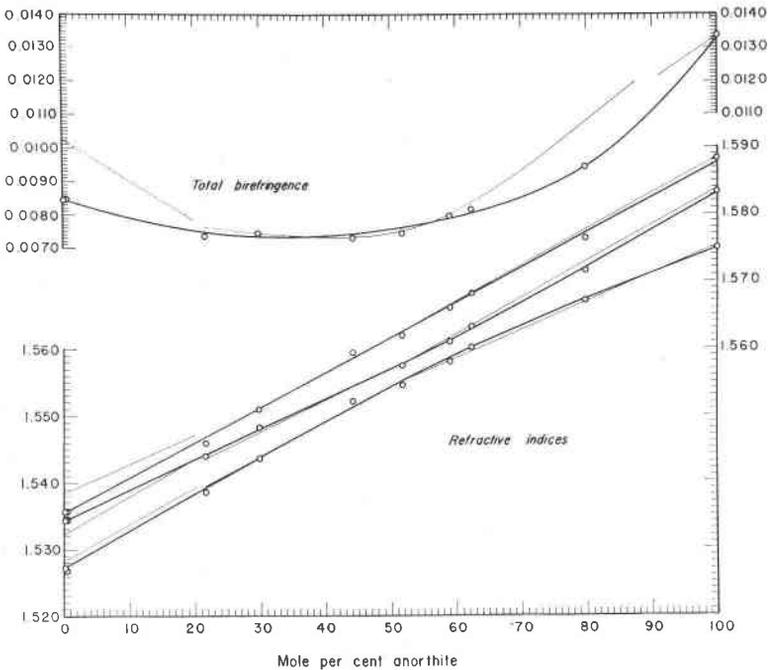
FIG. 3. Total birefringence and refractive indices for maximum high-temperature plagioclases (open circles and heavy curves). Light curves are for low-temperature plagioclases, taken from Smith (in Hess, in press).

The average values of total birefringence and refractive indices after final heat treatment are plotted in Fig. 3, and tentative curves are drawn for maximum high-temperature plagioclases. The curves shown for low-temperature plagioclases are from Smith (in Hess, in press); they are based on the same samples as those on which the 2V curve for low-temperature plagioclases in Fig. 2 is based, but to avoid confusion the determined values are not plotted. The significant fact here is that the difference in Nx between the low- and high-temperature modifications

appears to be very slight in the composition range An 0 to An 20, and negligible throughout the remainder of the range. Measurements of Nx therefore provide a reliable estimate of the composition of a plagioclase regardless of its structural state. In the composition range An 20 to An 100, any of the three principal indices provides a reliable composition estimate regardless of structural state.

3. *The temperature of the change from low- to high-temperature plagioclases*

The hydrothermal experiments of the present study show that plagioclases in the composition range An 30 to An 80 can be changed to maximum high-temperature modifications at temperatures as low as 990° C. In other experiments not reported here, it was found that slight, but measurable changes toward the high-temperature forms take place in natural plagioclases of composition An 20 and An 30 after long hydrothermal treatment at 690° C.; whether the changes would ever go to completion at this temperature is not known. Apart from these isolated observations, little was learned of the nature of the change from low- to high-temperature plagioclases or of the temperature at which it takes place under conditions of equilibrium.

4. *Comparison with results of others*

The present results compare well with those of Tuttle and Bowen (1950) as far as 2V of high-temperature sodic plagioclases is concerned, but differ from their tentative curve for 2V of high-temperature calcic plagioclases (cf. their Fig. 4 and present Fig. 2).

Kano (1955) has measured the refractive indices and 2V's of many sodic plagioclases from lavas. Following a suggestion by Chayes (1952), he assumed that Nx and Ny of high-temperature sodic plagioclases are not different from Nx and Ny of low-temperature sodic plagioclases, and determined the compositions of his samples by refractive index measurements. This assumption of course prevented him from discovering the small but real differences in Nx and Ny, and probably contributed some bias to his curve for Nz. However, the results of the present study in general agree well with Kano's.

Schwarzmann (1956) measured the optical properties of plagioclases in inclusions and ejecta in Tertiary volcanic rocks. Her determinations of Nx and Nz in the composition range An 20 to An 50 are lower by as much as 0.005 than the values determined here for high-temperature plagioclases of the same compositions; this represents a difference of as much as 6 per cent anorthite if the curves are used for composition determinations. The reason for the discrepancy is not apparent. It may be that the refractive indices of plagioclases which have been heated as

inclusions in lavas differ from those of plagioclases heated under laboratory conditions; this seems unlikely, because by other optical and structural criteria, sodic plagioclases from volcanic rocks are similar to those either made or heated in the laboratory (see, for example, Tuttle and Bowen, 1950, and Tuttle and Keith, 1954). Part of the discrepancy may result from the fact that Schwarzmann determined the compositions of most of her samples by optical methods, which is somewhat circuitous in a study aimed at discovering differences in optical properties.

Summary and Conclusions

The change in Nx accompanying the structural change from low- to high-temperature plagioclase is slight in the composition range An 0 to An 20 and negligible from An 20 to An 100. Ny and Nz change measurably in the composition range An 0 to An 20, but negligibly in the remainder of the composition range. Measurements of the principal refractive indices can therefore give a reliable estimate of the composition of a plagioclase regardless of its structural state.

The changes in 2V accompanying the structural changes are such that it may be used to distinguish low-temperature and high-temperature plagioclases of known composition in the composition ranges An 0 to about An 40 and An 60 to about An 90. This fact will be of use to the petrographer who does not have access to an x-ray diffractometer, by means of which a more rapid determination of the structural state of a plagioclase of known composition can be made.

Acknowledgments

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APPENDIX

ADDITIONAL OPTICAL DATA FOR LOW-TEMPERATURE PLAGIOCLASES

Measured values of 2V for low-temperature plagioclases are plotted in Fig. 2 of this paper. The optical measurements on all but four of these plagioclase samples have been published by the writer, either in Hess (in press) or in Table 3 of this paper. The writer's measurements of the optical properties of the remaining four samples have not previously been published, and do not appear in Table 3 because the samples in question were not heated. In the belief that accurate optical and x-ray data for chemically analyzed plagioclases will be of use in future studies, these four samples are described and the measurements are listed here. Unless otherwise noted, each value listed for optical properties was determined on a different grain by the methods referred to in the text. By the following x-ray criteria, the four samples are judged to be low-temperature plagioclases: (*a*) Values of $2\theta(131)-2\theta(1\bar{3}1)$ for samples 9(24), 12(97) and 13(92) are similar to those of Bushveld-type plagioclases (J. R. Smith and Yoder, 1956); (*b*) "c"-type reflections are diffuse but relatively intense in single-crystal oscillation photographs of grains from sample HGIF-AN-53 (cf. Gay, 1954).

(See tables A and B on following pages)

TABLE A. DESCRIPTION OF PLAGIOCLASE SAMPLES

Sample No.	Composition (mole %)*			Analyst	Occurrence and Locality	Contributor
	An	Ab	Or			
9(24)	47.7	48.8	3.5	L. C. Peck**	Anorthosite, Essex Co., N. Y.	R. C. Emmons
12(97)	54.5	43.3	2.2	L. C. Peck**	Plagioclase-rich rock of metamorphic origin, Eland, Wis.	R. C. Emmons
13(92)	54.9	42.8	2.3	L. C. Peck**	Same as 12(97), Tigerton, Wis.	R. C. Emmons
HGIF-AN-53	88.7	8.8	2.5	E. H. Oslund***	Large single crystal in vein-like mass in hornblende-actin olite schist, Olricksfjord Area, N.W. Greenland.	Allan H. Nicol

$$* \ An = 100 \left(\frac{Ca^{++}}{Ca^{++}+Na^{+}+K^{+}} \right); \qquad Ab = 100 \left(\frac{Na^{+}}{Ca^{++}+Na^{+}+K^{+}} \right);$$

$$Or = 100 \left(\frac{K^{+}}{Ca^{++}+Na^{+}+K^{+}} \right).$$

** Analysis in Emmons, R. C., et al. (1953), Selected Petrogenic Relationships of Plagioclase; Geol. Soc. Am. Memoir 52, Table 2, pp. 18–19.

*** Analysis in Smith, J. R. and Yoder, H. S., Jr. (1956), Variations in X-ray Powder Diffraction Patterns of Plagioclase Feldspars; Am. Min. 41, Table 3, p. 639.

TABLE B. OPTICAL AND X-RAY DATA

Sample	Nx	Ny and Nz means	$Nz-Nx$	$2V_z$	$2\theta(1\bar{3}1)$ $-2\theta(131)$ CuKα
	1.5515		0.00737	77.7°	1.79°
	1.5519		0.00745	78.5	1.79
	1.5524		0.00745	78.8	1.80
	1.5525		0.00754	79.0	1.80
	1.5526	Ny	0.00760	79.4	
	1.5526	1.5558	0.00762	79.8	
	1.5527		0.00764	80.0	
9(24)	1.5529	Nz	———	80.6	
	1.5529	1.5602		———	
(An 47.7)	1.5531				
	1.5531				
	1.5534				
	1.5539				

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TABLE B. (*Continued*)

Sample	Nx	Ny and Nz means	Nz−Nx	2V$_z$	2θ(131) −2θ(1$\bar{3}$1) CuKα
9(24)	Mean 1.5527		Mean 0.00752	Mean 79.2°	Mean 1.79°
(An 47.7)	Range 0.0024		Range 0.00027	Range 2.9°	Range 0.01°
	1.5562		0.00740	77.5°	1.82°
	1.5562	Ny	0.00742	77.6	1.82
	1.5562	1.5593	0.00748	77.7	1.82
	1.5563		0.00758	77.7	1.83
	1.5563	Nz	0.00758	78.4	——
	1.5563	1.5638	0.00762	78.5	
12(97)	1.5568		0.00778	78.9	
				79.1	
(An 54.5)					
	Mean 1.5563		Mean 0.00755	Mean 78.2°	Mean 1.82°
	Range 0.0006		Range 0.00038	Range 1.6°	Range 0.01°
	1.5563		0.00756	77.2°	1.80°
	1.5564	Ny	0.00760	77.3	1.80
	1.5564	1.5595	0.00761	77.7	1.81
13(92)	1.5566		0.00777	78.0	1.82
	1.5566	Nz	0.00786	78.1	——
		1.5642		78.5	
(An 54.9)				78.6	
	Mean 1.5565		Mean 0.00768	Mean 77.9°	Mean 1.81°
	Range 0.0003		Range 0.00030	Range 1.4°	Range 0.02°
	1.5714		0.01213	102.8°	2.22°
	1.5718		0.01213	103.6	2.23
	1.5719		0.01217	103.9	2.23
	1.5720	Ny	0.01224	104.6	——
HGIF-AN-53	1.5720	1.5794	——	——	
	1.5720				
	1.5722	Nz			
(An 88.7)	1.5722	1.5841			
	Mean 1.5719		Mean 0.01217	Mean 103.7°	Mean 2.23°
	Range 0.0008		Range 0.00011	Range 1.8°	Range 0.01°