THE AMERICAN MINERALOGIST, VOL. 50, JULY–AUGUST, 1965

A STUDY OF MEDIUM-CALCIC PLAGIOCLASE FELDSPARS FROM COAL-ASH SLAGS

H. J. KISCH, *Division of Coal Research, Commonwealth Scientific and Industrial Research Organization, Chatswood, New South Wales, Australia.*

ABSTRACT

Medium to calcic plagioclase feldspars formed in slags within a large boiler were shown by *x*-ray powder diffraction patterns to possess structural states comparable to those of volcanic plagioclase. The positions of the optical indicatrix axes in a number of twinned individuals were measured on a universal stage. The angular distances between corresponding optical vectors in subindividuals twinned according to various laws are given, and the orientation of the indicatrix in some of the twinned plagioclases is shown in stereographic projection. Comparison of these data with published figures and migration curves shows correspondence of the indicatrix orientations in the medium plagioclases (up to An_{65}) with the "high-temperature" curves; for the more calcic plagioclases from the slags, departures from these curves are evident, particularly with regard to the position of the Y indicatrix axes. Further measurements are desirable on twinned calcic plagioclase formed at controlled temperatures.

INTRODUCTION

This investigation forms part of a study of the behavior of the inorganic constituents of the clay- and FeS_2-rich brown coal from Leigh Creek (South Australia) when this fuel is burnt in pulverized-fuel boilers.

The major mineral in slags formed on the furnace walls is the plagioclase which forms the subject of this paper; other constituents are brown glass, fayalitic olivine, a clinopyroxene, quartz, magnetite and ilmenite.

The material studied consisted of two large samples (A and B) of furnace slag, formed during different runs, and of two smaller samples (C and D) taken during a boiler trial.[1] Plagioclase phenocrysts of a basalt (K-AU-18) from Mt. Kaputar, Nandewar Range, New South Wales, were studied for purposes of comparison.

This paper presents information on the variation with composition of the optical orientation of plagioclases from these furnace slags in the light of published migration curves, as well as on their twinning. Data on the "thermal state" of the plagioclases were obtained from the *x*-ray powder diffraction patterns (after Smith and Yoder, 1956 and Smith and Gay, 1958).

Köhler (1941, 1942) showed that the orientation of the optical indicatrix in plagioclase feldspars from volcanic rocks diverged from that of the "low-temperature" plagioclases of the same composition, on which the

[1] The reference numbers of these samples at the Division of Coal Research, CSIRO, are as follows: A, 15752; B, 17753; C, 18668; and D, 18669.

determinative curves of Reinhard and others were based. Since then, separate migration curves for the optical orientation in "high-temperature" plagioclases—covering part or the whole of the intermediate-calcic composition range—have been constructed by Tertsch (1942), Van der Kaaden (1951), Burri (1956), Slemmons (1962a), and others, most of them dealing with plagioclase from natural rocks only. Plagioclase with optics transitional between these two series has been studied by Muir (1955) and others. These differences in optical orientation between plagioclases of similar chemical compositions have been shown to reflect order-disorder effects in the structure of the plagioclase (see, for example, Gay, 1954, 1956; Gay and Bown, 1956; J. V. Smith and Gay, 1958; J. R. Smith and Yoder, 1956; Slemmons, 1962b).

Composition of the Plagioclase

The plagioclase in the slags occurs as well-developed plates up to 1 mm but generally less than 300 μ in diameter. Normal zoning is particularly evident in the larger crystals; the composition of the smaller crystals corresponds to that of the sodic rims of the larger. Intergrowth with magnetite, and association with glass and quartz, preclude concentration of the feldspar in a reasonably pure and representative form for chemical analysis. Phenocryst plagioclase from the basalt K-AU-18, concentrated by hand picking and magnetic separation, has been analyzed chemically. After correction for impurities (augite) a composition of about 54 mol % An is indicated.

The refractive indices of this plagioclase indicate a similar composition. These and the highest and lowest refractive indices measured in the plagioclase from each of the slags (A, B, and C), as well as the compositions using the determinative curves of Chayes (1952) and J. R. Smith (1958), are given in Table 1. The measurements, carried out by the immersion method in sodium light, are believed to be accurate to within ± 0.001.

In view of the proportion of small sodic crystals, and of the width of the sodic rims about the larger crystals, the average plagioclases in A, B, and C are estimated to have compositions of An_{45-50}, An_{65-70}, and about An_{70} respectively.

An attempt was also made to determine the average composition of the plagioclase using the infrared spectroscopic method of Thompson and Wadsworth (1957). Four mg of each of the powders used for x-ray diffraction (see below) was dispersed in 200-mg KCl disks and run on a Perkin-Elmer Model 521 grating infrared spectrophotometer. Most of the samples showed no marked absorption band in the 15.4–16.2 μ region, possibly owing to an insufficiently high concentration of the plagioclase. However, even in the relatively pure samples of plagioclase from K-AU-18 and the HCl-extracted portion 3 of Sample A the symmetry vibrational mode was found to be insufficiently sharp for accurate localization within the narrow range 15.95 μ (for An_{40}) to 16.16 μ (for An_{100}), although a double-expanded wavelength scale was used. From the results one cannot conclude more than that the average compositions are distinctly more calcic than An_{40}.

Structural or "Temperature" State of the Plagioclase

J. V. Smith and Yoder (1956) have shown that the angular reflection separations $2\theta(1\bar{3}1)-2\theta(220)$ and $2\theta(131)-2\theta(1\bar{3}1)$ in the *x*-ray powder

Table 1. Refractive Indices and Compositions of the Plagioclases Studied (Na Light)

Sample	α	β	γ	An-content (mol. %)
K-AU-18	1.557	1.560	1.564	52–55
A min.	1.550	1.554	1.559	42–44
A max.	1.556	1.560	1.565	53–55
B min.	1.562	1.566	1.571	64–68
B max.	1.569	1.576	1.581	82–86
C min.	1.564	1.568	1.572	68–71
C max.	1.566	1.570	1.575	72–76

diffraction patterns of plagioclases give an estimate of the structural state in the range An_0 to about An_{75}. Smith and Gay (1958) proposed the use of the difference between these separations, *i.e.*, $2\theta(131)+2\theta(220)-4\theta(1\bar{3}1)$, and of the reflection separation $2\theta(1\bar{1}1)-2\theta(\bar{2}01)$. The former varies more, and thus gives a more reliable indication of structural change in the range An_{20} to An_{70}; the latter provides a better estimate in the range $An_{70}-An_{100}$. The above reflection positions were measured on a Philips diffractometer using Cu-Kα radiation. Divergent and scatter slits were 1°, receiving slit 0.1 mm, scan speed $\frac{1}{4}$°/min, and chart speed 8 cm/°2θ. In some cases greater accuracy was achieved using a decade counter at settings 0.02°2θ apart.

X-ray diffraction patterns were taken from two different samples of the phenocryst plagioclase from K-AU-18, and from concentrates of plagioclase of Slags A and B obtained by float-sink in bromoform, magnetic separation, and a combination of these methods; treatment with 5N HCl for several hours was applied in preparing one concentrate (A/3). The angular separations obtained are given in Table 2.

On the basis of the average composition of An_{54} the average values for the separations of the phenocryst plagioclase from K-AU-18 indicate a "high-temperature" form, corresponding to the dry synthetic to volcanic plagioclase of Smith and Yoder (1956) and Smith and Gay (1958).

The values for the plagioclases of the two slags show more agreement with the curves for volcanic feldspars than with those for plagioclases synthesized in the dry way, *i.e.* they are not in the "maximum high-temperature" state. This reflects: (1) the fact that the slag plagioclase was

TABLE 2. ANGULAR SEPARATIONS FOR THE PLAGIOCLASE FELDSPARS

Sample/conc.	$2\theta(1\bar{1}1) - 2\theta(\bar{2}01)$	$2\theta(1\bar{3}1) - 2\theta(220)$	$2\theta(131) - 2\theta(1\bar{3}1)$	$2\theta(131)+2\theta(220) - 4\theta(1\bar{3}1)$
K-AU-18/1	0.83, 0.82	1.07, 1.08	2.03, 2.03	0.96, 0.95
K-AU-18/2	0.84, 0.83	1.06. 1.06	1.96, 1.97	0.90. 0.91
A/1	0.85	1.23	1.90	0.68
A/2	0.88, 0.87	1.17, 1.18	1.85	0.68
A/3	0.87, 0.87	1.21, 1.20	1.85, 1.84	0.64, 0.64
B/1	0.77, 0.79	1.02, 1.04	2.02	0.99
B/2	0.79, 0.79	1.06, 1.05	—	—
B/2a	0.78, 0.77	—	—	—
B/2b	0.76, 0.77	1.00, 1.02	—	—

Plagioclase concentrates:

A/1—bromoform-float fraction; A/2—the more magnetic part of the bromoform-sink fraction; A/3—extracted with 5N HCl.

B/1—bromoform-float fraction; B/2—another bromoform-float fraction; from part of this concentrate the fractions magnetic at 0.25 amp. (B/2a) and non-magnetic at 0.6 amp. (B/2b) were separated in a Frantz isodynamic separator.

The concentrates B/2, 2a, and 2b contained appreciable clinopyroxene, the strong 2.99 Å peak of which affects the position of the $1\bar{3}1$ plagioclase peak at 3.02Å; moreover, the 131 plagioclase peak was rather broad. For these concentrates therefore only the reflection separation $2\theta(1\bar{1}1)-2\theta(\bar{2}01)$ was considered.

formed at temperatures much below those at which the plagioclases of Schairer[1] were synthesized, *i.e.* slightly below the solidus of the dry system Ab-An; and possibly (2) the increasing order due to the less rapid quenching and/or to the content of K_2O the effects of which are insufficiently known. It may be noted that the calcic "high-temperature" curve of Burri is based on K-free synthetic plagioclase and that few chemically analyzed natural bytownites contain more than 1.5 mol % Or (Deer, *et al.*, 1963, Table 17), whereas the most calcic of the three Linosa feldspars

[1] Used by Smith and Yoder (1956) and Smith and Gay (1958).

(An_{54}) used for the construction of all published "high-temperature" curves contains 3.2 mol % Or.

Evidence on the temperature of crystallization of plagioclase is available from measurements of the viscosity/temperature characteristics of the slags and observations on the mineralogy of one of the slags after melting and crystallization at controlled temperatures.

The viscosity/temperature characteristics of Slag A and Slag B were studied by Boow (1965). These slags flowed slowly down the walls of a furnace at temperatures of about 1400° C. and were finally quenched at the bottom of the furnace. Whilst flowing on the walls the upper layers were probably at a viscosity not exceeding about 10^6 poises, which corresponds to temperatures of not less than 1050° C. for Slag A and not less than 1100° C. for Slag B. Additional information on this point was obtained from experiments in which powdered samples of Slag A were fused, crystallized in recrystallized-alumina crucibles at controlled temperatures for several hours in a nitrogen atmosphere, and quenched. Mineralogical compositions similar to that in the original material (pale brown glass, well-twinned plagioclase $An_{58\rightarrow45}$, Fe-rich olivine) were obtained as a result of crystallization at 1100–1050° C.

Twinning in the Plagioclase

The plagioclase from the slags is well twinned according to the albite, Carlsbad, and albite-Carlsbad (Roc Tourné) laws, and occasionally the acline A law. Polysynthetic twinning is common, and often more than one twin law is represented in an individual. The composition planes of the Carlsbad and albite-Carlsbad twins often diverge from (010). The twin lamellae have widely varying thicknesses, but very thin lamellae (less than 2 μ thick) are uncommon. The twinning has all the evidence of being primary.

Cross- and T-shaped intergrowths are common, with the (010) cleavages of the constituent crystals often roughly at right angles to one another. The composition planes—which, however, are often irregular—sometimes make angles of about 45° with the (010) cleavages. It was initially thought that they might be "Banat intergrowths," which Burri (1963) confirmed to be Baveno twins [with either (021) or ($0\bar{2}1$), as both twinning and composition planes]. However, measurement of several of these intergrowths on the universal stage did not support this assumption: the (001) and (010) cleavages of the constituent individuals were not mutually parallel and the symmetry plane, if one could be constructed at all, did not include the crystallographic *a*-axis [100]. It therefore seems that most of these cross- and T-shaped intergrowths are not twins.

Measurements on the Universal Stage: Procedure

The optical vectors of a number of plagioclase individuals of twinned crystals were measured on a Leitz 4-axis universal stage in thin sections of the slags cut at various orientations. The positions of the indicatrix axes were measured in adjoining parts of two or more subindividuals. All measurements were made on the cores of the crystals, which are often homogeneous in composition over a comparatively large area; in many crystals the optical vectors of the more sodic rims were also measured. To avoid measuring zones with different composition occurring on both sides of the composition plane, it was preferred to make measurements on subindividuals separated by composition planes through the center of the crystals, and the measurements were made close to the composition plane. The Becke test was applied to check possible differences in refringence on both sides of the composition plane. The position of each vector was averaged from five or ten readings and rounded off to 0.5°. In view of the small difference between the refractive index of the glass hemispheres (1.557) and the β value of the plagioclase (1.554–1.576) no correction was made.

In addition, the position of the cleavage—and generally also the positions of the composition plane (010) and if possible of the (001) cleavage and of one of the optic axes—were located. All measured directions were plotted on a Wulff net. Subindividuals in which the averaged positions for two optical vectors were not within $90° \pm 2°$ were discarded. The twinning axes were then located. The size of the triangle formed by the points midway between the positions of the corresponding optical directions in the two subindividuals could be used as an additional criterion to test the reliability of the measurements. Moreover, for optical vectors in two subindividuals measured in both core and rim of a zoned crystal, the two twinning axes have to coincide. Whenever the position of the (010) cleavage has been measured accurately, the twinning axes of Carlsbad and albite-Carlsbad twins must lie parallel to it and the twinning axis of albite twins normal to it.

The angular distances $X \wedge X'$, $Y \wedge Y'$, and $Z \wedge Z'$ between the pairs of corresponding optical vectors for each twin were measured from the stereogram across the twinning axis (Table 3).

Finally, the optical indicatrix of one of each pair of subindividuals of albite or albite-Carlsbad twins was rotated by 180° about the twinning axis to coincide with that of the other and projected on the plane normal to the *c*-axis [001]; for Carlsbad twins, of which [001] itself is the twinning axis, the 180° rotation is unnecessary. In general, these operations were carried out only when the position both of [001] and of (010) had been located optically, *i.e.* for which three subindividuals twinned according to

Table 3. Angular Distances between Pairs of Corresponding Optical Vectors $X \wedge X'$, $Y \wedge Y'$, and $Z \wedge Z'$ for the Various Twin Laws[1]

Sample	Thin section	Individual (c): core (r): rim	Albite law (degrees)			Carlsbad law (degrees)			Albite-Carlsbad lawZ (degrees)			Other twin laws (degrees)			Approximate composition[2] in An (for the "temperature" state indicated)
			$X_1 \wedge X_{1'}$	$Y_1 \wedge Y_{1'}$	$Z_1 \wedge Z_{1'}$	$X_1 \wedge X_2$	$Y_1 \wedge Y_2$	$Z_1 \wedge Z_2$	$X_1 \wedge X_{2'}$	$Y_1 \wedge Y_{2'}$	$Z_1 \wedge Z_{2'}$	$X \wedge X'$	$Y \wedge Y'$	$Z \wedge Z'$	
B	9184a	I				66½	175	113½							70–72(HT)
		II				63½	172	115½							66–69(HT)
		III							153	53	134				82–87(HT)
		IV							152	51	138				87(HT)
	9184b	Ia				65	161	119							63(HT)
	9428	Ia	120	125½	85	69	175½	112½	148½	53½	137				75–80(HT), 74–75(HT), 81(HT)
		Ib				67	168	116½							66(HT)
		Ic(?)										Acline A: 116	122	88	75–80(HT)
		II(r)				65	168	115½							68(HT)
		IIIa/(c)							143	51	144				60–70(HT)
		IIIa/(r)							114	75½	147½				56(HT)
		IIIb				63	~180	114							69(HT)
		IV(c)	118½	133	83	68	~176	110½	149	52½	140				77–82(HT), 77(HT), 81(HT)
		IV(r)	126½	126	77	65½	162	116½	144½	54	139½				65–69(HT), 70(HT-t), 72(HT)
		V(c)	121	131	82½	65½	176	114½	148	54½	141				72–77(HT), 74(HT), 64–80(HT)
		V(r)	124	129	78½	62	172	116½	139	61½	137½				65–70(HT), 68(tr), 66(HT)
		VIa/(c)	127	120½	80½										66–68(HT)
		VIa/(r)	132	122	74½										62(HT)–65(tr)
		VIb/(c)	121	130½	83										70–77(HT)
		VIb/(r)	134	122	74½										63(HT)

TABLE 3.—(*continued*)

Sample	Thin section	Individual (c): core (r): rim	Albite law $X_1 \wedge X_1'$ (degrees)	Albite law $Y_1 \wedge Y_1'$	Albite law $Z_1 \wedge Z_1'$	Carlsbad law $X_1 \wedge X_2$ (degrees)	Carlsbad law $Y_1 \wedge Y_2$	Carlsbad law $Z_1 \wedge Z_2$	Albite-Carlsbad law $X_1 \wedge X_{2'}$ (degrees)	Albite-Carlsbad law $Y_1 \wedge Y_{2'}$	Albite-Carlsbad law $Z_1 \wedge Z_{2'}$	Other twin laws $X \wedge X'$ (degrees)	Other twin laws $Y \wedge Y'$	Other twin laws $Z \wedge Z'$	Approximate composition[2] in % An (for the "temperature" state indicated)
A	9175	Ia/(c)	166½	114½	66										47–49(HT)
		Ia/(r)	171	116	64½										45–47(HT)
		Ib/(c)	164½	111½	70										48–51(HT)
		Ib/(r)	177	116	64										41–46(HT)
		II(c)				89	118	125							49(HT)
		II(r)				93	109	126							47–48(HT)
		III	173½	127	54½										41(HT-tr)
	9662	I			71½			119	89	102½	144½				57(HT)
		II(c)				74	147½	120							56–58(HT)
A (run 6)	9833	I	152½	118	69	81	128½	111	111½	80	145				53–54(HT), 52–53(HT), 54–55(HT)
D	9677	I							139½	60½	136½				67(HT)
		II										Acline A:			
												134	118	83	65(tr)
C	9678	I(c)				70½	168	111							67–70(HT)
		I(r)				70½	152	119							60(HT)
		II				62	171	118½							70(HT-tr)
		III(c)	124	125	81										67(HT)–72(tr)
		III(r)	126½	127	78½										64(HT)–70(tr)
		IV	130	127	77										63(HT)–69(tr)
K-AU-18	X	I	156	121½	62½	78	125½	128½	107	82	148				52(HT-tr), 53(LT-tr), 53(HT-tr)
	9793	I							120	73	144½				57(HT)
		IIa	158½	118	66										48–49(HT)
		IIb	150	118	69½										54(HT)
K-AU-18	9793a	I	148	121	69	81	128½	123	108	79½	149½				55(HT), 53(HT-tr), 54(tr)
		I	153			80			106½						53(HT), 54(HT), 53(HT)
		II	152	117½	68	80½	130½	122	106	86½	148				54(HT), 53–54(HT), 52½(HT)

[1] Angular distances are given between the vector positions averaged from 5 to 10 measurements and rounded off to 0.5°.
[2] Approximated by interpolation between the values given by Burri (1956).

different laws—of which one had to be either the Carlsbad or the albite-Carlsbad law—were measured. Only in a few instances was use made of (010) as obtained from measurement of a cleavage or composition plane. Whenever the positions of corresponding directions were not exactly symmetrical about their respective twin axes, and consequently did not exactly coincide on 180° rotation, the average position was taken. Figures 1, 2a, 2b, and 3 are sections of a synoptic stereogram on the plane normal to [001] showing these average indicatrix orientations. Migration curves by Burri (1956) and Muir (1955, Fig. 7) are included for comparison.

Orientation of Optical Indicatrix and Determination of Composition

The angular distances $X \wedge X'$, $Y \wedge Y'$, and $Z \wedge Z'$, as given in Table 3 for the various twin laws, were compared with the data compiled by Burri (1956, Tables 8 and 9).[1] For some of the twins investigated the composition and the temperature "modification" can be derived without difficulty. However, for many twins—particularly in the bytownites of Slag B—there was no composition and temperature "modification" for which all three angles showed good correspondence. In such cases the composition range in Table 3 is that for which there is a minimal difference between the measured angles and the literature values. In interpolating, the optics were assumed to be of the "high-temperature" type except where another state gave a better fit for the various angles. Also, slightly more consideration was given to angles between two directly measured corresponding directions than to those between one directly measured and one constructed or to those between two constructed directions. As different vectors were directly measured in different individuals, the approximate compositions are not strictly comparable: they indicate only the *order* of the An content.

Several workers have observed that for "high-temperature" An_{60-75} the orientation of the optical indicatrix is very similar to that for "low-temperature" An_{65-80}. The synoptic stereograms on the plane normal to the *c*-axis (Figs. 1, 2a, and 3) show that the more sodic plagioclases measured fall within 1° of the "high-temperature" migration curves, whereas the positions of the indicatrix axes of the bytownites evidently differ from the published migration curves. Most conspicuous is the distinct tendency of the Y positions to fall on the "ultra-high-temperature" side of the "high-temperature" curve, *i.e.* closer to $\perp[001]/(010)$.

[1] Burri's values for the angular distances $Y_1 \wedge Y_{1'}$ (for the albite law) and $X_1 \wedge X_2$, $X_1 \wedge X_{2'}$ and $Z_1 \wedge Z_2$, $Z_1 \wedge Z_{2'}$ (for the Carlsbad and albite-Carlsbad laws) are not measured over the twinning axes but are the supplementary values.

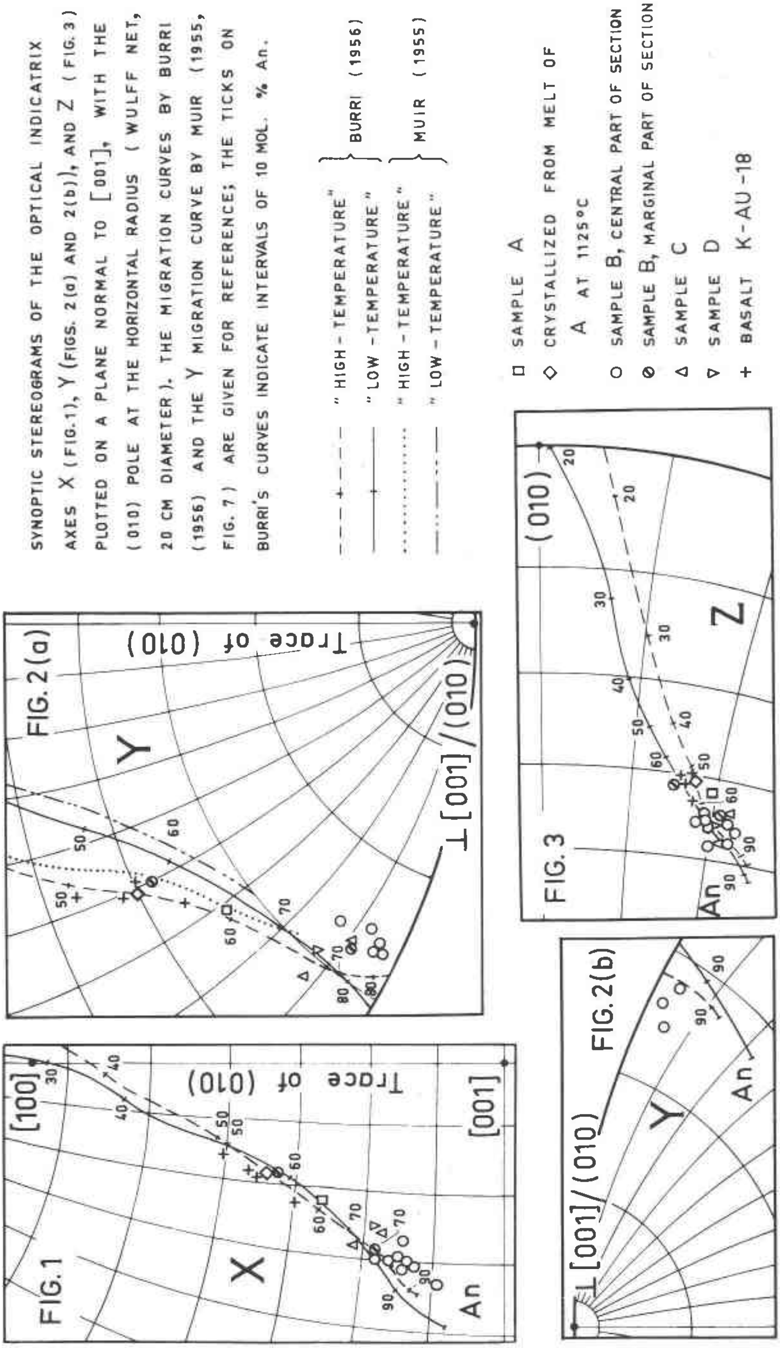
SYNOPTIC STEREOGRAMS OF THE OPTICAL INDICATRIX AXES X (FIG.1), Y (FIGS. 2(a) AND 2(b)), AND Z (FIG. 3) PLOTTED ON A PLANE NORMAL TO [001], WITH THE (010) POLE AT THE HORIZONTAL RADIUS (WULFF NET, 20 CM DIAMETER). THE MIGRATION CURVES BY BURRI (1956) AND THE Y MIGRATION CURVE BY MUIR (1955, FIG. 7) ARE GIVEN FOR REFERENCE; THE TICKS ON BURRI'S CURVES INDICATE INTERVALS OF 10 MOL. % An.
"HIGH-TEMPERATURE"
"LOW-TEMPERATURE"
BURRI (1956)
"HIGH-TEMPERATURE"
"LOW-TEMPERATURE"
MUIR (1955)
□ SAMPLE A
◇ CRYSTALLIZED FROM MELT OF A AT 1125°C
○ SAMPLE B, CENTRAL PART OF SECTION
⊘ SAMPLE B, MARGINAL PART OF SECTION
△ SAMPLE C
▽ SAMPLE D
+ BASALT K-AU-18
FIG. 1
X
[100]
[001]
Trace of (010)
An
FIG. 2(a)
Y
Trace of (010)
⊥[001]/(010)
FIG. 2(b)
⊥[001]/(010)
An
FIG. 3
Z
(010)
An

FIG. 1–3

The migration trends of the three axes of the optical indicatrix will now be briefly discussed with reference to the published migration curves, as well as the divergences from the published figures of the angular distances $X \wedge X'$, $Y \wedge Y'$, and $Z \wedge Z'$ for the various twin laws.

X. The X-axis positions of the medium plagioclases are scattered about the two migration curves, which in this range of composition lie very close together: all points fall within $1\frac{1}{2}°$ of the "high-temperature" migration curve. The X-axis positions for the plagioclases more calcic than An_{65}, however, lie almost without exception closer to [001] than do the corresponding points on Burri's migration curve—on the average by about $1\frac{1}{2}$–2° but in one instance by 4°. This divergence is particularly reflected in the angle $X_1 \wedge X_2$ in Carlsbad twins (with *c* as twinning axis). According to Burri (1956) and Slemmons (1962a) respectively, this angle attains minimum values of 67.7° and 66.6° for "high-temperature" plagioclase of labradorite-bytownite composition, the values for An_{80} being 69.8° and 69.0°. In the twinned cores of plagioclase crystals of Slag B the angles found were between 69° and 62° (Table 3). The $X_1 \wedge X_{2'}$ angles in albite-Carlsbad twins in those crystals are higher than expected and indicate compositions consistently more calcic than the interpolated values. The values of the angle $X_1 \wedge X_{1'}$ (albite law) correspond to those of Burri: the shift of these X positions from the curves for the calcic plagioclases seems to be roughly parallel to the trace of (010), the symmetry plane of this law. The plotted X directions can be regarded as lying in a band limited by two small circles with radii of 56° and 60° about a center situated on the primitive circle roughly 36° from the pole (010). This point would approximately correspond to the pole (120), given as the spherical center of the X positions of natural and synthetic high-plagioclases by Glauser and Wenk (1957), who give 54° and 57° as the radii of the limiting small circles.

Y. The Y positions of the measured medium plagioclases lie essentially between the "high-temperature" migration curve of Burri (1956) and that of Muir (1955, Fig. 7), which for this range of composition lie up to 2° apart. As already mentioned, the positions of the calcic labradorites and bytownites of Slag B tend to lie closer to $\perp$[001]/(010) than Burri's curve. This is reflected in the values found for $Y_1 \wedge Y_{1'}$ (albite twins), which are consistently higher than expected—sometimes as high as 130°. By contrast, the variation given by Burri is from only 121.0° for An_{70} to 125.0° for An_{90} (Slemmons's angles are slightly lower); the values for the angle $Y_1 \wedge Y_{2'}$ (albite-Carlsbad twins) are correspondingly too low (51–$54\frac{1}{2}°$ in cores of plagioclase crystals from Slag B).

It seems that the Y migration curve for the calcic "high-temperature" plagioclase feldspars lies at a slightly lower angle to the (010) plane than indicated by Burri. For the construction of that author's "high-temperature" curve in the An_{70} range only the synthetic labradorite-bytownite prepared by Tertsch (1942) was available. Tertsch himself gives the orientation of the indicatrix in this plagioclase with reserve, as it is based on measurement of only two twinned sections. Burri (1956), mentioning the uncertainty of his "high-temperature" curve in this range, points out that his calculated Euler angles ϕ and ψ may well be too high; the present observations would correspond to smaller Euler angles for the calcic plagioclases from the slags than for the comparable points on Burri's "high-temperature" curve. Most of the Y positions of calcic plagioclases plotted would be within 1° of the continuation of Muir's "high-temperature" migration curve—which is given up to about An_{70}.

Z. The positions of this indicatrix axis fall in practically all cases within 2° of Burri's "high-temperature" migration curve; there is a tendency for the points to lie to the "low-temperature" side of that curve. The plotted Z directions for the bytownites of Slag B indicate somewhat more sodic compositions than those interpolated between the values for all three angular distances between corresponding indicatrix axes in twins: up to An_{82} and up to An_{87} respectively for the most calcic cores. This is particularly apparent from a comparison of the values for $Z_1 \wedge Z_1$, in albite twins and of $Z_1 \wedge Z_{2'}$ in albite-Carlsbad twins with the values for $X_1 \wedge X_{1'}$ and $X_1 \wedge X_{2'}$: the angular distances between the Z positions give almost consistently more sodic compositions.[1]

Conclusions

The accuracy of the measurements reported here is limited by the zonal structure of the plagioclase. However, if the precautions described above are taken the measurements can be used to indicate the trend of the migration curves and their lateral departures from published curves. In the absence of chemical data on the composition of individual crystals,

[1] *Optic axial angles.* In a number of the plagioclase subindividuals 2V was obtained by single-axis measurement, which gives rather low reproducibility and the values are therefore not stated. According to Slemmons (1962b), 2V is of questionable value in determining the structural state in plagioclases more calcic than An_{40}. The general indication is that for the labradorites the axial angles correspond to the values given by Smith (1958) for the compositions derived from the orientation of the optical indicatrix. In the bytownites the values for $2V_z$ tend to be a few degrees higher than those given by the curves for the interpolated compositions; in the central parts of crystals from Slag B values between 85° and 95° were common. This could mean either that the composition of the bytownites is slightly more calcic or that they are not in the "highest-temperature" state.

shifts in the direction of the curves themselves are less apparent and can only be recognized by comparison between all three indicatrix axis positions of an individual (or the angular distances between corresponding axes in twins of various laws).

Some general conclusions can be drawn:

(1) The orientation of the indicatrixes in the medium plagioclases up to about An_{65} corresponds to that given by the "high-temperature" migration curves of Burri.

(2) Departures from these curves occur for the more calcic plagioclase from the slags. This effect was most apparent in lateral departures of the Y positions, and to a lesser extent of the X positions, from the respective "high-temperature" migration curves. Moreover, there were indications of a shift of the X positions roughly parallel to (010), while the Z positions seemed to lie slightly nearer the pole of (010) and to be displaced roughly parallel to (010) from the "high-temperature" curve.

(3) These displacements could be tentatively regarded as a rotation of the relative position of the indicatrixes of these calcic plagioclases by up to 3° from the position indicated by the "high-temperature" migration curves. The approximate center of rotation would fall near (010) in the acute angle between [100] and [001]; this center would lie close to the pole of ($\bar{1}01$).

(4) For more accurate data on the orientation of the indicatrix in calcic plagioclases from slags, measurements will be necessary on larger and less zoned twinned crystals formed at known temperatures.

Acknowledgments

The author wishes to acknowledge the help given by his colleagues, especially by Dr. R. A. Durie (chemical analysis of one plagioclase sample, and infrared spectroscopic work) and by Dr. J. Dunderdale and Dr. M. Kossenberg (*x*-ray powder diffraction patterns). Dr. G. H. Taylor and Dr. J. Boow critically read the manuscript.

References

Boow, J. (1965) Viscosity/temperature characteristics of some Australian coal-ash slags in the range 1100° to 1600° C. *Jour. Inst. Fuel*, **38**, 3–12.

Burri, C. (1956) Charakterisierung der Plagioklasoptik durch drei Winkel und Neuentwurf des Stereogramms der optischen Orientierung für konstante Anorthit-Intervalle. *Schweiz. Mineral, Petrog. Mitt.* **36**, 539–592.

——— (1963) Die sogenannte Banater Verwachsung der Plagioklase. *Schweiz. Mineral. Petrog. Mitt.* **43**, 71–80.

Chayes, F. (1952) Relations between composition and indexes of refraction in natural plagioclase. *Am. Jour. Sci. Bowen Vol.*, 85–105.

Deer, W. A., R. A. Howie and J. Zussman (1963) *Rock-forming Minerals*. Vol. 4. *Framework Silicates*. Longmans, London.

GAY, P. (1954) The structures of the plagioclase feldspars. V. The heat-treatment of lime-rich plagioclases. *Mineral. Mag.* **30,** 428–438.

——— (1956) The structures of the plagioclase feldspars. VI. Natural intermediate plagioclases. *Mineral. Mag.* **31,** 21–40.

——— AND M. G. BOWN (1956) The structures of the plagioclase feldspars. VII. Heat-treatment of intermediate plagioclases. *Mineral. Mag.* **31,** 306–313.

GLAUSER, A. AND E. WENK (1957) Über Gesetzmässigkeiten im Verlaufe der Migrationskurven der Plagioklase (Fedorow-Methode). *Schweiz. Mineral. Petrog. Mitt.* **37,** 180–197.

KAADEN, G. VAN DER (1951) Optical studies on natural plagioclase feldspars with high- and low-temperature optics. Dissertation, University of Utrecht.

KÖHLER, A. (1941) Die Abhängigkeit der Plagioklasoptik vom vorangegangenen Wärmeverhalten (Die Existenz einer Hoch- und Tieftemperaturoptik). *Mineral. Petrog. Mitt.* **53,** 24–49.

——— (1942) Drehtischmessungen an Plagioklaszwillingen von Tief- und Hochtemperaturoptik. *Mineral. Petrog. Mitt.* **53,** 159–179.

MUIR, I. D. (1955) Transitional optics of some andesines and labradorites. *Mineral. Mag.* **30,** 545–568.

SLEMMONS, D. B. (1962a) Determination of volcanic and plutonic plagioclases using a three- or four-axis universal stage. *Geol. Soc. Am., Spec. Paper.* **69.**

——— (1962b) Observation on order-disorder relations of natural plagioclase. I. A method of evaluating order-disorder. *Norsk Geol. Tidsskr.* **42,** 533–554.

SMITH, J. R. (1958) The optical properties of heated plagioclases. *Am. Mineral.* **43,** 1179–1194.

——— AND H. S. YODER (1956) Variations in x-ray powder diffraction patterns of plagioclase feldspars. *Am. Mineral.* **41,** 632–647.

SMITH, J. V. AND P. GAY (1958) The powder patterns and lattice parameters of plagioclase feldspars. II. *Mineral. Mag.* **31,** 744–762.

TERTSCH, H. (1942) Zur Hochtemperaturoptik basischer Plagioklase. *Mineral. Petrog. Mitt.* **54,** 193–217.

THOMPSON, C. S. AND M. E. WADSWORTH (1957) Determination of the composition of plagioclase feldspars by means of infrared spectroscopy. *Am. Mineral.* **42,** 334–341.

Manuscript received, December 14, 1964; accepted for publication, March 19, 1965.