The optical orientation of labradorite from County Down (Ireland) determined by the Fedorov method.

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LABRADORITE of exceptional purity, occurring as phenocrysts in two basaltic dikes just below the lighthouse at St. John's Point, Ardglass, County Down, Northern Ireland, was described by Professor A. Hutchinson and myself in 1912.[1] The refractive indices for sodium-light were determined on an Abbé-Pulfrich total-reflectometer. Carefully selected material was analysed by Mr. G. G. Knighton and by Mr. M. C. Burkitt, and the specific gravity of the material analysed was determined. The results obtained were as follows:

Composition, $Ab_{33}An_{62}Or_5$.
Specific gravity compared with water at 4° C., 2·706.
Refractive indices for Na-light, α 1·5630, β 1·5665, γ 1·5712.
Optic axial angle, 2V 81° 48′ (calc. from refr. indices); opt. positive.
Angle measured between cleavages (001) : (010) = 85° 57′.
Extinction-angles measured on cleavage fragments:
 on *c* (001), −11° to trace of *b* cleavage;
 on *b* (010), −23° to trace of *c* cleavage.

In 1923 S. Tsuboi,[2] working on the same felspar, remeasured the refractive indices for a variety of wave-lengths, and also determined the positions of the optic axes A and B in two sections of which the orientation was known. He obtained:

α 1·5623, β 1·5663, γ 1·5713.
2V 83° 52′ (calculated from refractive indices).
2V 83° 45′ (calculated from positions of A and B).
 (For λ = 589·3 $\mu\mu$ (Na) at 21·5° C.)

[1] A. Hutchinson and W. Campbell Smith, On sericite from North Wales and on penninite and labradorite from Ireland. Min. Mag., 1912, vol. 16, pp. 267–271.

[2] S. Tsuboi, Optical dispersion of three intermediate plagioclases. Min. Mag., 1923, vol. 20, pp. 101–107.

To these data are now added determinations of the optic orientation and the optic axial angle made by the Fedorov method as developed by Nikitin,[1] Duparc and Reinhard,[2] and Berek.[3] Measurements have been made on fifteen phenocrysts contained in three thin sections from the rock-specimens which supplied the material for analysis. On five of the phenocrysts measurements of extinction-angles have also been made. The apparatus used is the large universal revolving stage constructed by the firm of Ernst Leitz, Wetzlar, Germany, and fitted to a Leitz polarizing microscope (Stand GM) with rotating stage. Hemispheres of refractive index 1·554 were employed. The illuminant was a 58 candle-power, 100 watt gas-filled Stella lamp used with a water-filled 600 c.c. flask as condenser, and screened with blue-tinted tracing-paper,[4] the illumination being controlled on the lines recommended by M. Berek.[5]

The notation adopted in recording the measurements is almost identical with that used in the memoir by Duparc and Reinhard, and by M. Gysin in his recent papers. The principal vibration-directions are represented by n_α, n_β, n_γ, corresponding to n_p, n_m, and n_g of French authors.

Pairs of individuals of normal hemitropes (e.g. albite twin) are indicated by 1 and 1′, 2 and 2′, and the optic axes A and B in individual 1 are represented by A′ and B′ in individual 1′. Pairs of individuals in a parallel hemitrope (e.g. Carlsbad twin) are indicated as 1 and 2, and the twinned position of the optic axes A and B by A^2 and B^2.

Twin-axes are represented by T-A (corresponding to Π of Berek and A of Gysin) and poles of planes of association are denoted by P: e.g. T-$A_{1-1'}$ means the twin-axis of individuals 1 and 1′; P_{1-2}, the pole of the plane of association of the two individuals 1 and 2.

The results of the measurements are given in terms of the co-ordinates of the poles of twin-axes and planes of association with reference to the three principal vibration-directions of the two individuals of a twin, and the mean of the two sets of co-ordinates is taken; e.g. T-$A_{1-1'}$ (1) means

[1] W. W. Nikitin, La méthode universelle de Fédoroff. French translation by L. Duparc and V. de Dervies, Genève, Paris, and Liège, 1914, 516 pp. and atlas.

[2] L. Duparc and M. Reinhard, La détermination des plagioclases dans les coupes minces. Mém. Soc. Phys. Hist. Nat. Genève, 1924, vol. 40, pp. 1–149, 59 text-figs., 18 pls. [Min. Abstr., vol. 3, p. 34.]

[3] M. Berek, Mikroskopische Mineralbestimmung mit Hilfe der Universaldrehtischmethoden. Berlin, 1924, 168 pp., 55 text-figs., 7 pls. [Min. Abstr., vol. 2, p. 365.]

[4] 'Bluish glaucous', see R. Ridgway, Color standards and nomenclature. Washington, 1912, pl. 42.

[5] Loc. cit., p. 38.

that the co-ordinates of the twin-axis between 1 and 1′ are measured on to the poles of n_α, n_β, n_γ, for individual 1.

These co-ordinates can then be plotted on a stereographic projection drawn on tracing-paper, and identical in diameter with the projection drawn by Duparc and Reinhard (loc. cit., pl. 9) which gives the curves of migration of the poles of twin-axes, planes of association, and crystal-faces of the plagioclase series plotted with reference to n_α, n_β, and n_γ as axes.

The twin-axis will be found either to coincide with the pole of the face of association (normal hemitrope) or to lie in the plane of the face (parallel hemitrope or complex[1]). This decides the kind of twin-law. By superposing the projection on which the position of the twin-axis has been plotted on the Duparc and Reinhard diagram one can find on which of the migration curves any points plotted fall, and thereby determine conclusively the nature of the twin-law or the indices of a face, and at the same time obtain a fairly close estimate of the composition of the felspar. In some cases the projections might be capable of more than one possible solution, and it is important to obtain the co-ordinates of as many poles as possible in order to test the completeness of the coincidences of poles and curves. In the extremely simple example now under consideration these difficulties do not arise.

The results for the poles of the twin-axes are of a higher degree of accuracy than those for the poles of planes of association, and the latter are recorded chiefly as proof of the nature of the twin-laws involved.

Crystal 1.—Part of a large crystal with numerous parallel twin-lamellae belonging to four individuals. No satisfactory measurements were made on one set (2–2′) as the lamellae were exceedingly thin.

		n_α.	n_β.	n_γ.	
T-A_1	(1) ...	+73°	+62°	−35°	$\text{T-A}_{1-1'}$ coincides with $\text{P}_{1-1'}$;
	(1′) ...	+73	−61	+35	∴ a normal hemitrope;
	Mean ...	73	61½	35	$\text{T-A}_{1-1'}$ found to correspond
$\text{P}_{1-1'}$	(1) ...	+75	+60	−35	with albite twin-axis, and
	(1′) ...	+70	+63½	−35	$\text{P}_{1-1'}$ with (010).
	Mean ...	72½	62	35	
$\text{T-A}_{1-2'}$	(1) ...	+59½	−35½	−73	$\text{T-A}_{1-2'}$ found to be twin-axis
	(2′) ...	+59	−35½	−75	of albite-Carlsbad complex.
	Mean ...	59¼	35½	74	
P_{1-2}	(2′) ...	+72	+65	−31½	(010).

V_1 41°, $V_{1'}$ 37½°, $V_{2'}$ 40½°. Average for 2V 79°, corresponding to 58½ % An. Maximum extinction-angle in zone perp. to (010), 35·2°.

[1] 'Complex': term used by Fedorov for a combination of a normal hemitrope with a parallel hemitrope having the same plane of association.

Crystal 2.—Section nearly normal to (010), showing lamellae belonging to two individuals.

			n_α.	n_β.	n_γ.	
$T\text{-}A_{1-1'}$	(1)	...	+74°	−61°	+34°	$T\text{-}A_{1-1'}$ coincides with $P_{1-1'}$ and is the twin-axis of an albite twin.
	(1′)	...	+74	−62	+33	
	Mean	...	74	61½	33½	
$P_{1-1'}$	(1)	...	+75	−64	+32	
	(1′)	...	+73	−58	+36	
	Mean	...	74	61	34	

V_1 43°, $V_{1'}$ 42°. Average for 2V 85°, corresponding to 63 % An.
Maximum extinction-angle in zone perp. to (010), 34°.

Crystal 3.—Large phenocryst showing a Carlsbad twin, both individuals of which are twinned on the albite law, and one of them showing also lamellae which were proved to be pericline (or 'acline-A'). The crystal is rather strongly zoned. Satisfactory measurements were obtained only on two individuals of the Carlsbad twin.

			n_α.	n_β.	n_γ.	
$T\text{-}A_{1-2}$	(1)	...	+38°	+70°	+59°	$T\text{-}A_{1-2}$ twin-axis of Carlsbad twin, and lies in the plane P_{1-2}.
	(2)	...	+38	−69	+59	
	Mean	...	38	69½	59	
P_{1-2}	(2)	...	−74	+61	+33	(010).
P_{2-3}	(2)	...	−66	+47	−52	P_{2-3} plane of assoc. of pericline twin (or acline-A).

V_1 43°, V_2 38°. Average for 2V 81°, corresponding to 59½ % An.
Angle between optic axes B and B_2 in two individuals of Carlsbad twin, 52°.
Angle between the planes of the optic axes in the same two individuals, 39°.
Maximum extinction-angle in zone perp. to (010), 37°.

Crystal 4.—A small crystal with very rounded corners showing albite and pericline lamellae. This crystal did not afford very accurate measurements.

			n_α.	n_β.	n_γ.	
$T\text{-}A_{1-1'}$	(1)	...	−75°	+61°	−33°	$T\text{-}A_{1-1'}$ twin-axis of albite twin, coinciding with $P_{1-1'}$ (010).
	(1′)	...	−78	+60	−32	
	Mean	...	76½	60½	32½	
$P_{1-1'}$	(1)	...	−76	+61	−33	
	(1′)	...	−77½	+60	−32	
	Mean	...	77	60½	32½	(010).
$T\text{-}A_{1-2}$	(1)	...	+48	+75	+46	$T\text{-}A_{1-2}$ twin-axis of pericline (or acline-A twin).
	(2)	...	+48	+75	+48	
	Mean	...	48	75	47	
P_{1-2}	(1)	...	+66	−44	−53½	P_{1-2} plane of assoc. of pericline (or acline-A).

V_1 37½°, corresponding to 52 % An.

Crystal 5.—Part of a large phenocryst showing twinning on albite and Carlsbad laws.

		n_α.	n_β.	n_γ.	
$T\text{-}A_{1-2}$	(1) ...	$+36\frac{1}{2}°$	$+71°$	$+61°$	$T\text{-}A_{1-2}$ was found to lie in the plane of P_{1-2}, and to be a twin-axis of a Carlsbad twin.
	(2) ...	$+37$	$+69$	$+60$	
	Mean ...	37	70	$60\frac{1}{2}$	
$T\text{-}A_{2-2'}$	(2) ...	$+73$	$+60$	-36	$T\text{-}A_{2-2'}$ was found to be nearly coincident with P_{1-2}, and to be a twin-axis of an albite twin.
	(2′) ...	$+72\frac{1}{2}$	$+60$	-36	
	Mean ...	73	60	36	

V_1 $37\frac{1}{2}°$, V_2 40°, $V_{2'}$ $38\frac{1}{2}°$. Average for 2V 77°, corresponding to 56 % An.
Angle between the planes of the optic axes in 1 and 2, 40°.
Angle between the optic axes B and B^2, 55°.
" " " " B^2 and $B^{2'}$, 53°.
" " " " B and $B^{2'}$, 14°.

Crystal 6.—Part of a large phenocryst bounded by faces of the forms (010), (110), (100), showing albite lamellae. Satisfactory readings were obtained only for the pole of the albite twin-axis.

		n_α.	n_β.	n_γ.	
$T\text{-}A_{1-1'}$	(1) ...	$+72\frac{1}{2}°$	$-61°$	$+35°$	$P_{1-1'}$ was found to be nearly coincident with $T\text{-}A_{1-1'}$, which is an albite twin-axis.
	(1′) ...	$+72\frac{1}{2}$	-61	$+35$	
	Mean ...	$72\frac{1}{2}$	61	35	

$2V_1$ 73°. $2V_1$ (measured on another part of the crystal) 79°.
Average for 2V 76°, corresponding to 54 % An.

Crystal 7.—A phenocryst with rounded edges showing albite lamellae. Parts of edges, and patches near centre, of slightly different composition to the main part of the crystal. From measurements made on the main part:

		n_α.	n_β.	n_γ.
$T\text{-}A_{1-1'}$	(1) ...	$-68°$	$+61\frac{1}{2}°$	$+37\frac{1}{2}°$
	(1′) ...	$+68$	$+61\frac{1}{2}$	$+37$
	Mean ...	68	$61\frac{1}{2}$	37

This crystal gave good readings for 2V. $2V_1$ main part 84°; edge and patches $74\frac{1}{2}°$. $V_{1'}$ main part 41°. Average for 2V in main part 83°, corresponding to $61\frac{1}{2}$ % An.
Angle between optic axial planes in 1 and 1′ in main part of crystal, 57°.
Angle between optic axes A and A′, 64°.
Angle between optic axes A and B′, 65°.

Crystal 8.—Part of a phenocryst showing many very thin albite lamellae and one slightly broader on which measurements were made. The measurements are not considered to be very reliable as difficulty was experienced in locating the plane of vibration $\perp n_\alpha$ in the lamellae.

		n_α.	n_β.	n_γ.	
$T\text{-}A_{1-1'}$	(1) ...	$-71°$	$+60°$	$-36°$	$P_{1-1'}$ was found to be nearly coincident with $T\text{-}A_{1-1'}$, which is an albite twin-axis.
	(1′) ...	[+70]	-61	$+36$	
	Mean ...	71	$60\frac{1}{2}$	36	

V_1 44°, $V_{1'}$ 44°. Average for 2V 88°, corresponding to 66 % An.
Angle between optic axial planes in 1 and 1′, 58°.
Angle between optic axes A and A′, 72°.
Maximum extinction in zone perpendicular to (010), 38°.

Crystal 9.—Part of a phenocryst showing albite lamellae.

		n_α.	n_β.	n_γ.	
$T\text{-}A_{1-1'}$	(1) ...	+67°	+62°	$-37\frac{1}{2}$°	$P_{1-1'}$ was found to coincide with $T\text{-}A_{1-1'}$ which is an albite twin-axis.
	(1′) ...	+67	+62	$-37\frac{1}{2}$	
	Mean ...	67	62	$37\frac{1}{2}$	

$2V_1$ 87°, $V_{1'}$ 44° (approx.). Average for 2V $87\frac{1}{2}$°, corresponding to 66 % An.
Angle between planes of optic axes 1 – 1′, 57°.
Angle between optic axes B and B′, 35°.
Angle between optic axes A and B′, 64°.

Crystal 10.—Part of phenocryst showing albite lamellae. Measurements not very reliable as the position of the plane ⊥ n_α in individual 1′ could not be confirmed.

		n_α.	n_β.	n_γ.	
$T\text{-}A_{1-1'}$	(1) ...	–76°	+60°	+32°	$P_{1-1'}$ is nearly coincident with $T\text{-}A_{1-1'}$ which is an albite twin-axis.
	(1′) ...	–74	+60	–36	
	Mean ...	75	60	34	

V_1 45°, $V_{1'}$ 40°. Average for 2V 85°, corresponding to 63 % An.
Angle between optic axial planes of 1 and 1′, 59°.
Angle between optic axes A′ and B, 55°.
Maximum extinction-angle in zone perpendicular to (010), 35·5°.

Crystal 11.—A phenocryst with rounded edges showing albite lamellae. Very similar to crystal 7. Parts of edges and patches in centre of different composition to main part. For the main part of the crystal :

		n_α.	n_β.	n_γ.	
$T\text{-}A_{1-1'}$	(1) ...	$+68\frac{1}{2}$°	+61°	+38°	$P_{1-1'}$ coincides approximately with $T\text{-}A_{1-1'}$ which is an albite twin-axis.
	(1′) ...	–68	$+60\frac{1}{2}$	+37	
	Mean ...	68	61	$37\frac{1}{2}$	

V_1 $40\frac{1}{2}$°, $2V_{1'}$ $81\frac{1}{2}$°. Average for 2V 81°, corresponding to 60 % An.
Extinction in section ⊥ n_γ, $39\frac{1}{2}$°.
Angle between optic axial planes of 1 and 1′, 59°.
Angle between optic axes A and A′, 66°.
Angle between optic axes A and B′, 61°.
For edges and irregular patches in the centre the co-ordinates are :

		n_α.	n_β.	n_γ.
$T\text{-}A_{1-1'}$	(1) ...	+73°	+61°	+36°
	(1′) ...	–71	+60	+36
	Mean ...	72	$60\frac{1}{2}$	36

Also for these parts of the crystal : V_1 39°, $2V_{1'}$ 78°, corresponding to $56\frac{1}{2}$ % An.
Extinction in section ⊥ n_γ, $42\frac{1}{2}$°.

Crystal 12.—Part of a phenocryst showing twinning on albite and Carlsbad laws.

			n_α.	n_β.	n_γ.	
T-A_{1-2}	(1)	...	41°	$65\frac{1}{2}$°	$57\frac{1}{2}$°	T-A_{1-2} is found to lie in the plane P_{1-2}; it is a Carlsbad twin-axis.

No other measurements of co-ordinates were obtained on this section.
V_1, 38°, V_2 40°. Average for 2V 79°, corresponding to $57\frac{1}{2}$ % An.

The co-ordinates with reference to the vibration-directions n_α, n_β, n_γ, of the albite twin-axis perpendicular to (010) were obtained from ten of the crystals measured. The arithmetic means of the values are

	n_α.	n_β.	n_γ.
	71°	61°	$36\frac{1}{2}$°
variations	±4°	±1°	±2°

Plotted on a large size stereographic net,[1] these points form a group of seven of which the centre of mass is about

73° 61° 35°

and a smaller group of three (crystals 9, 11, and 13) with centre of mass at

68° $61\frac{1}{2}$° $37\frac{1}{2}$°

When referred to the diagram of Duparc and Reinhard (loc. cit., pl. 9) these points are found to lie near the part of the curve for (010) which corresponds to about 65 An, but they all lie off the actual curve on the side nearer the centre of projection.

M. Gysin[2] and others have remarked previously on the fact that the projections of (010), plotted from a great number of determinations of basic plagioclases, are found to be well to the right of the curve for (010) as originally drawn in the Duparc and Reinhard diagram. Further measurements on analysed felspars may prove that the curve needs slight corrections, but it is probable that these displacements towards the centre of the projection are due to the influence of potash.

Values for V, half the optic axial angle, were obtained from every

[1] A stereographic net with six-inch radius and graduated to single degrees is printed at the University Press, Cambridge, for the Mineralogical Department of the University. This is reduced by permission of the Hydrographic Department of the United States Navy from the net prepared in 1888 by the late Admiral C. D. Sigsbee.

[2] M. Gysin, Note sur l'étude de quelques caractères des plagioclases. Compte Rendu Soc. Phys. Hist. Nat. Genève, 1922, vol. 39, p. 73.

crystal, thirty-eight measurements being recorded. The average of these is 41°, hence 2V 82°. The crystals are optically positive.

The variation in composition among the phenocrysts examined is indicated by the percentage of anorthite deduced from values 2V using Duparc and Reinhard's curves (loc. cit., p. 12, fig. 2). It ranges from 52 % An on the acid borders and patches of crystal 7 to 66 % An in crystal 8. Differences of composition of the same order have been recorded for phenocrysts in basalts both by M. Gysin in a basalt from Madagascar and by A. Borloz[1] in tholeiites from the Ural Mountains.

The results of the chemical analyses by Knighton and Burkitt may be taken to represent the average composition of the phenocrysts. Consequently the average values of the Fedorov measurements for (010) and V may be taken to represent accurately their correct values for a plagioclase of the composition $Ab_{33}An_{62}Or_5$.

The co-ordinates for (010) and the values of V were the only data which were obtainable from all of the crystals examined. Two values were obtained for the co-ordinates of the Carlsbad twin-axis and one for the complex albite-Carlsbad. Such isolated measurements on one or two crystals cannot be correlated with the average composition obtained by analysis.

Other values which were measured on four or five crystals are:

Angle between optic axes B and B′ in two individuals of an albite twin, 49°; this being the average for five crystals for which 2V averages $81\frac{1}{2}$°, corresponding to 60 % An.

Angle between the optic axes A and B′ in two individuals of an albite twin, 61°; this being the average for four crystals for which 2V averages $84\frac{1}{2}$°, corresponding to $62\frac{1}{2}$ % An.

Maximum extinction-angle in zone perpendicular to (010), average 36° for five crystals; for which 2V averages 83°, corresponding to $61\frac{1}{2}$ % An.

As regards the frequency with which the three twin-laws albite, Carlsbad, and pericline appear, the results show that, of fifteen crystals examined, all show albite twinning; one shows albite, Carlsbad, and pericline; four show albite and pericline; four albite-Carlsbad; and six albite alone. In every instance of Carlsbad twins the face of association was found to be (010), i. e. the 'Carlsbad-A' twin of Duparc and Reinhard.

[1] A. Borloz, Contribution à l'étude des plagioclases des roches d'épanchement. Univ. Genève, Faculté Sci. 1924, Thèse no. 744, p. 49. [Min. Abstr., vol. 3, p. 292.]

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