The effects of heat on the optical orientation of plagioclase felspars.

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A CONSPICUOUS feature of all published diagrams, showing the results of the determination of a number of plagioclase felspars by the Fedorov method, is the pronounced scattering of the poles. They lie not only on the curves of the determinative stereogram,[1] but on either side of them, and, in fact, occupy a belt, varying in different instances, and in different positions along the length of the same curve, from 3 to 8 mm. in width. These belts usually contain, but are not symmetrically disposed to, the curves. This phenomenon has been remarked upon by Reinhard,[2] Spaenhauer,[3] and Manolescu,[4] who have considered four possible explanations of the scattering of the poles :

(*a*) That it may be due to inaccurate measurements, arising either from faulty observation, or from the use of inaccurate instruments.

(*b*) That the determinative curves are themselves incorrect.

(*c*) That the morphological directions determined are not true crystallographic directions, but vicinal directions.

(*d*) That the orientation of the indicatrix in plagioclase felspars is dependent not only on the anorthite content, but is influenced also by some other chemical component, as for example, potash.

In a previous paper [5] I have reviewed the work of these investigators, and shown that after making due allowance for the factors

1 M. Reinhard, Universal Drehtischmethoden. Basel, 1931, plate II. [M.A. 4-435.]

2 M. Reinhard, loc. cit., pp. 105–112.

3 F. Spaenhauer, Über das Ergebnis von Messungen an synthetischen Plagioklasen mit Hilfe des Universaldrehtisches. Schweiz. Min. Petr. Mitt., 1933, vol. 13, pp. 356–365. [M.A. 5-437.]

4 G. Manolescu, Über die Lage der morphologischen Bezugsrichtungen bei Plagioklasen und ihre Verwendbarkeit zur Bestimmung des Anorthitgehaltes. Ibid., 1934, vol. 14, pp, 452–463.

5 C. T. Barber, Mem. Geol. Surv. India, 1936, vol. 68, pp. 121–292.

enumerated above, there remains a residue of scattering of the poles for which previous hypotheses fail to account. In 1931, Barth[1] described an appreciable alteration of both the position and shape of the indicatrix in labradorite under the influence of heat, and stated also, that except for a slight increase in the axial angle, the properties of albite and oligoclase are not changed by heat. On the basis of these observations, I suggested that physical changes, and particularly the effects of heat, might be capable of explaining the residue of scattering of the poles for which previous hypotheses were unable to account. In November 1935, therefore, a series of experiments were commenced with the object of ascertaining the amount and variability, both in magnitude and direction, of the displacement of the indicatrix in plagioclase felspars under the influence of heat. The experiments conducted are by no means exhaustive, but as I have been unable to reproduce Barth's results, and am unable to continue the investigation at the present time, it appears desirable to place on record a brief account of the results obtained.

Experiments have been conducted on albite from Alp Rischuna, Switzerland[2]; andesine from Esterel, France[3]; labradorite from County Down, Ireland[4]; and anorthite from Japan.[5]

The first experiments were conducted on serial sections of andesine and labradorite, an initial section or sections being taken to establish the optical orientation of the untreated material; contiguous segments were used for heating, and thin sections of them ground after heat treatment. Four experiments on these lines, two each with andesine and labradorite, revealed that the apparent change in the optical orientation, due to heat treatment, was so slight as to be commensurate with the scattering of the poles derived by determina-

[1] T. W. F. Barth, Permanent changes in the optical orientation of feldspars exposed to heat. Norsk Geol. Tidsskrift, 1931, vol. 12, pp. 57–72. [M.A. 5-218.]

[2] W. J. Lewis, On crystals of albite from Alp Rischuna, and pericline twins from Fibbia, Switzerland. Min. Mag., 1915, vol. 17, pp. 178–188; and S. Kôzu, The dispersion phenomena of albite from Alp Rischuna, Switzerland. Ibid., pp. 189–192.

[3] A. Lacroix, Minéralogie de la France. Paris, 1896, vol. 2, pp. 180–182 (analysis, p. 177).

[4] W. Campbell Smith, The optical orientation of labradorite from County Down (Ireland) determined by the Fedorov method. Min. Mag., 1928, vol. 21, pp. 543–551.

[5] K. Makino, Anorthite crystals from Otaru in Hokkaidō. Beitr. Min. Japan, 1915, no. 5, pp. 287–288. [M.A. 1-136.]

tion of a number of *untreated* segments. In subsequent experiments, therefore, thin sections, varying from twice to three times standard thickness, were prepared, their original optical orientation determined by the Fedorov method, and the thin section floated off for heat treatment. After heat treatment, the sections, or remains of them, were remounted, and the optical orientation redetermined. In this way, scattering of the original poles was eliminated and their displacement by heat treatment more accurately discernible.

In all the experiments, segments or thin sections of the felspars were suspended in small platinum bags in a platinum resistance quenching furnace, previously raised to the required temperature. Owing to the deterioration of thermal couples maintained at high temperatures for protracted periods, the thermal couple was not retained in the furnace during the actual heat treatment of the felspars, but tests carried out for periods of three days before and after the experiments show that the variation in temperature is well within the limits of $\pm 5°$ C., and all the experiments were conducted at a temperature of $1000 \pm 5°$ C. The duration of heating varied from 200 to 500 hours, and at the end of these periods the material was immediately chilled by dropping into mercury. The cohesion of the various felspars investigated under this somewhat drastic treatment varied considerably. The labradorite, even in thin section, disintegrated hardly at all, and cleavage, which was not discernible in the original material, was not developed by the heating and rapid chilling. The other felspars, in which cleavage was developed in the original material, disintegrated to a greater or less extent, the andesine being the most prone to disintegration, not only parting along the cleavage but also breaking into irregular fragments. In no case, however, was the disintegration so complete that the larger fragments were too small for determination.

All the felspars determined were twinned according to the albite law, in association, in some instances, with parallel twinning on (010). As the albite composition-plane was common to them all, the change in optical orientation under the influence of heat has been expressed in terms of the displacement of the pole of (010) with reference to fixed optical vectors, that is to say, in the same terms as plate II of Reinhard's determinative stereograms (loc. cit.). For ready reference, this stereogram is reproduced here as fig. 1, on the reduced scale of 10 cm. diameter. The other figures, however, in which the (010) curve of this stereogram is reproduced, are on the original scale of

20 cm. diameter, which is the smallest scale on which the displacement of the poles is readily discernible.

In establishing the pole of (010), the position of the albite symmetry-plane was employed instead of the morphological composition-

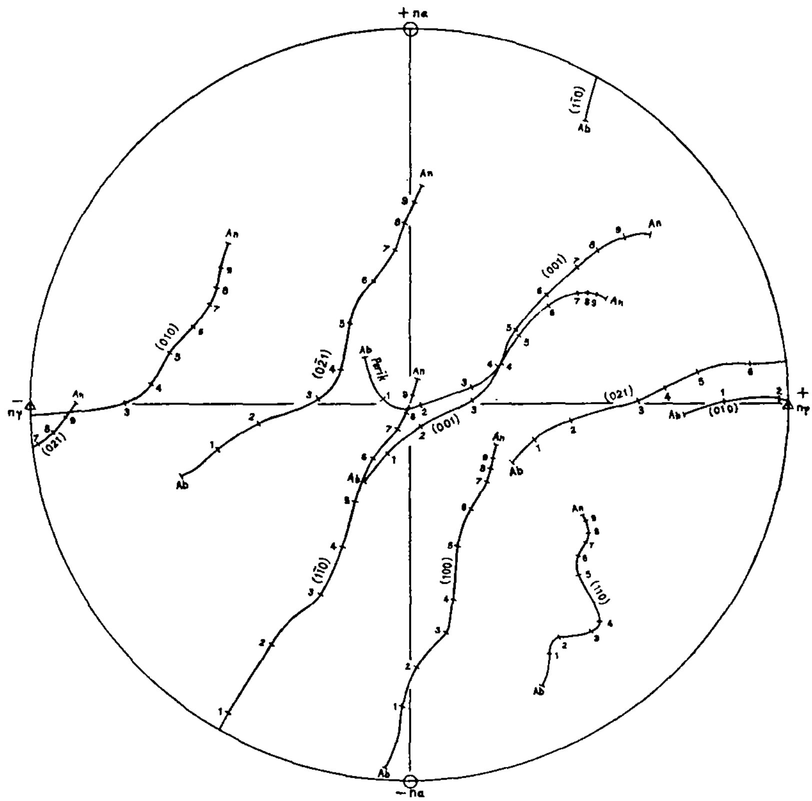

FIG. 1. Fedorov-Nikitin stereogram, after M. Reinhard. Showing the migration of crystallographic poles with reference to fixed optical vectors.

plane, in order to eliminate the effects of vicinal phenomena.[1] Where other morphological directions were recognizable these were also determined, but in order to avoid the multiplication of text-figures, their poles have not been reproduced. For the same reason, the whole of the data have been expressed in tabular form, but text-

[1] C. T. Barber, loc. cit., pp. 238–241.

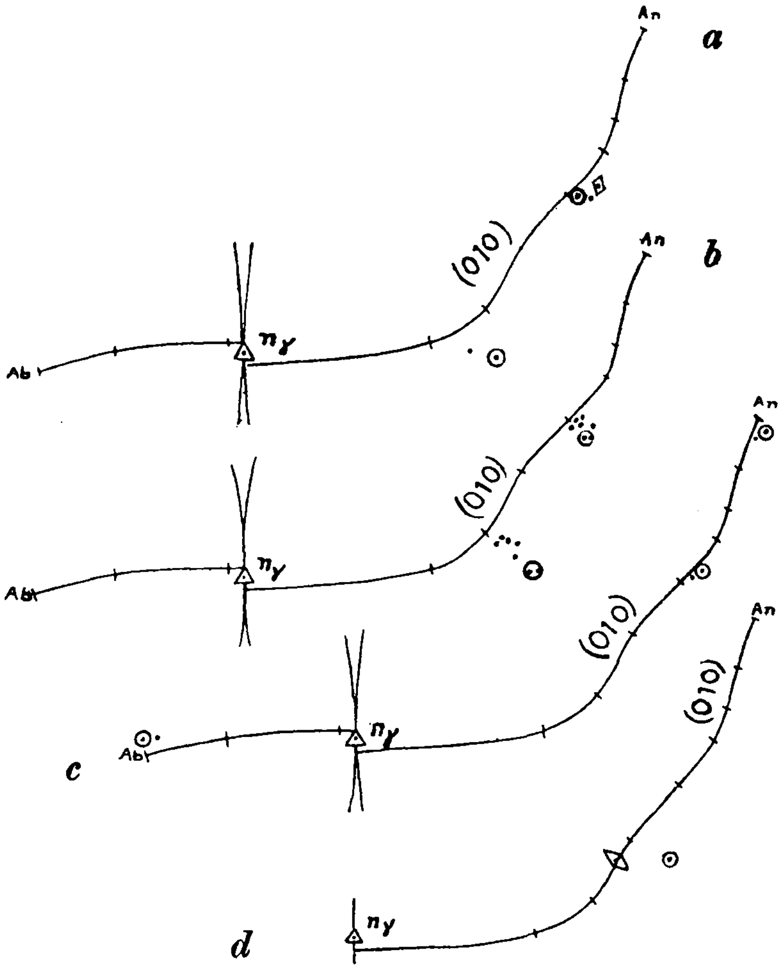

FIG. 2. Showing the effects of heating at 1000° C. on the position of the (010) pole in various felspars.

(*a*) Andesine and labradorite for 200 hours, and labradorite for two periods of 200 hours. Original poles as plain dots; after 200 hours as ringed dots; after 200 + 200 hours as lozenged dot.

(*b*) Andesine and labradorite for 404 hours. Original poles as plain dots; after heating as ringed dots.

(*c*) Albite, labradorite, and anorthite for 500 hours. Original poles as plain dots; after heating as ringed dots.

(*d*) Barth's data on heating labradorite at 1000° C. for 300 hours. Original pole as lozenged dot; after heating for 300 hours as ringed dot.

figures illustrating the effects of heating for 200, 404, and 500 hours, are also given, so that the direction of displacement of the poles may be more precisely recognizable. Figs. 2 *a–c* embody, respectively, the data given in lines 3, 6, and 8; 4 and 9; and 1, 10, and 12, of table I. Lines 2, 4, 5, and 9, of the table, refer to the initial experiments in which the original optics of the material treated were not determined, and in these cases the position of the final poles of (010) are compared with the collected poles of the untreated material. Fig. 2 *b* reproduces in diagrammatic form the data given in lines 4 and 9 of the table, and is given principally to show the magnitude of the field of scattering of the poles of five specimens each of untreated andesine and labradorite.

A study of table I and figs. 2 *a–c* reveals that, except in the initial experiments, in which the final pole of (010) after heat treatment is compared with the field of five poles, derived by determination of *other* sections of the same felspars, the maximum apparent displacement due to heating and rapid chilling is 2°. This displacement is so slight that I hesitate to suggest that it has any objective reality. The accuracy of determination by the Fedorov method has been discussed by Spaenhauer (loc. cit., p. 359), who states that the poles of the same felspar, determined four times, on different universal stages, and by two observers, showed a field of scattering of 2 mm. diameter. In this particular work, Spaenhauer was concerned with the determination of anorthite, and in this portion of the stereogram, 2 mm. is equivalent to an angular distance of 2°. The apparent displacement of the poles due to heat treatment cannot, therefore, be said to be greater than the normal degree of experimental error. If, however, the direction of apparent displacement is constant, one would be tempted to regard it as real. In the case of labradorite (lines 5–10 of table I), on which the most experiments have been conducted, and which was the most satisfactory material for determination, the direction is not constant. In the two initial experiments, the apparent displacement is away from the curve and to the right. While there may be some doubt as to the magnitude of the displacement, as it is compared, not with an individual pole, but with a field of five poles of untreated material, there is no doubt about its direction, as the final pole lies farther from the curve than the most distant original pole. In the subsequent experiments with labradorite, in which the optics of the same section were determined both before and after heat treatment, the direction of apparent

TABLE I. Felspars heated at 1000±5° C.

	Anorthite content ± 3%.	Duration of heating, in hours.	Angular displacement of pole of (010).	Direction of displacement in stereogram.	Remarks.
1.	5%	500	2°	To the left, sub-parallel to curve.	Confirmed by displacement of pole of (001).
2.	40	200	3° from centre of field of original poles.	Away from and to right of curve.	Confirmed by displacement of pole of (001).
3.	40	200	2°	Away from and to right of curve.	Confirmed by displacement of the pericline pole.
4.	40	404	3½° from centre of field of original poles.*	Away from and to right of curve.	Confirmed by displacement of the pericline and (001) poles.
5.	60	200	2° from centre of field of original poles.	Away from and to right of curve.	—
6.	60	200	2°	Towards the curve and to the left.	Confirmed by displacement of the pericline pole.
7.	60	200	1½°	Towards the curve and to the left.	—
8.	60	200+200	2°	Sub-parallel to the curve and towards the anorthite end.	Initial displacement (200 hours) 2° towards the curve.
9.	60	404	2½° from centre of field of original poles.	Away from and to right of curve.	—
10.	60	500	2°	Sub-parallel to the curve and towards the anorthite end.	—
11.	95	200	None.	—	Confirmed by the absence of displacement of the pericline twin-axis.
12.	95	500	2°	Sub-parallel to the curve and towards the anorthite end.	—

* The pole of a second specimen, determined after heat treatment, lay 5° from the centre of the field of original poles.

displacement is variable. In two experiments, in both of which the section was heated for 200 hours, the apparent displacement is towards the curve, but reheating one of these sections for a further period of 200 hours (line 8 of table I and fig. 2 *a*) produced a comparable apparent displacement in the opposite direction. The apparent displacement after heating for 500 hours (fig. 2 *c*) is sub-parallel to the curve, instead of sub-normal to it, as in the previous cases, and is comparable, both in magnitude and direction, to the cumulative effect of treatment for two periods of 200 hours (fig. 2 *a*).

In a number of cases I have stated, in the last column of table I, that the results are confirmed by determinations of the poles of (001) and the pericline composition-plane. I would emphasize, however, that this is confirmation only that the morphological directions have been accurately determined, as any error, in the determination of the optical elements, would produce comparable displacements of all the morphological poles in the stereogram. My final view, therefore, is one of doubt as to whether the very slight apparent displacements observed, and recorded in table I, have any objective reality. In view of this conclusion, it is hardly logical to discuss the variability of the displacement under varying durations of heat treatment, but if they have any reality, the conclusion that their variability is very slight appears inevitable, and it is certainly far too small to be of any value as a 'geological thermometer'.

The conclusion, that the change of the optical orientation, under the influence of heat, is so slight as to be unrecognizable with any degree of certainty, is in strong contrast with Barth's work on labradorite. This observer states (loc. cit., p. 69): 'Labradorite, Klovsteinen, Sondeled.—Several heating experiments the duration of which varied from 48 to 300 hours were carried out on this mineral. These experiments show definitely that a pronounced change of both the position and shape of the optical indicatrix takes place. These changes are shown by the projection.' The projection given embodies the results of heating at 1000° C. for 300 hours. It is a projection 7·8 cm. in diameter on [010]. The better to compare the magnitude and direction of the displacement of the indicatrix with my own results, I have carefully enlarged this projection to 20 cm. diameter, and transposed it to a projection perpendicular to n_β, to conform to plate II of Reinhard's stereograms, and the other figures given in this paper. The resulting poles of (010) are shown in their relationship to the appropriate curve in fig. 2 *d*.

The angular displacement of the pole of (010) in this instance is 6°, which is much greater than the normal degree of experimental error. It is regrettable, however, that Barth has not given more experimental details in his paper, as the rapidity of cooling, and the degree of temperature variation during heating, may be important factors, the effects of which, together with those of temperatures both higher and lower than 1000° C., I hope to investigate at some future date.

Barth also investigated the effects of heat on albite and oligoclase, and states that, except for a slight increase in the optic axial angle, the properties of these minerals are not changed by heating. This is in agreement with the one experiment I have conducted with albite.

During my investigations of the effects of heat on the optical orientation of the felspars, I paid attention also to its effects on the optic axial angle, the results of which are given in table II.

TABLE II. Variations in the optic axial angle of felspars due to heating at 1000 ± 5° C.

	Composition of felspar, anorthite % ± 3%.	Value of 2V before heat treatment.	Duration of heating, in hours.	Value of 2V after heating.
1.	5	79	500	80
2.	40	88 to 90	200	−88
3.	40	−88	200	−85
4.	40	88 to 90	404	−88
5.	60	80	200	78
6.	60	81	200	76
7.	60	80	200	77
8.	60	81	200 + 200	76
9.	60	81	404	77
10.	60	80	500	77
11.	95	−76	200	−77
12.	95	−78	500	−78

The optic axis is the least accurately determinable of the optical vectors by the Fedorov method, and the variations, noted in table II, are within the normal degree of experimental error. Since, however, they are consistent, one is inclined to attribute some reality to them. The most surprising of these data is that relating to albite (line 1 of table II), since E. Spencer[1] has recorded an increase of 6·8° in the

[1] E. Spencer, A contribution to the study of moonstone from Ceylon and other areas and of the stability-relations of the alkali-felspars. Min. Mag., 1930, vol. 22, p. 346.

optic axial angle of Amelia albite, after heating to 950–1100° C. for six hours. As I have conducted only one experiment on albite, I regard my result with caution, but an increase of the order of magnitude recorded by Spencer could not have escaped detection by universal-stage methods.

I am indebted to my former teacher, Prof. M. Reinhard, of the University of Basel, for the specimens of andesine investigated; to Prof. C. E. Tilley, for the hospitality of his department at Cambridge, for the other specimens investigated, for his personal interest in the whole of the work, and for criticizing the manuscript.