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Ferriferous orthoclase from Madagascar.

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Introduction.

In 1916 Kôzu recorded the fact that a specimen of yellow Madagascar orthoclase, subsequently shown by Seto (1923) to contain 2·93% Fe_2O_3, had an optic axial angle of 20° 17′ (Na_D light) with the optic axial plane parallel to (010). This observation is in apparent conflict with the useful curves relating 2V to composition for alkali-felspars compiled by Dr. O. F. Tuttle (1951, 1952). These curves were designed to show how the felspars fall into several more or less distinct series, rather than as an aid to the precise determination of composition, which in fact must be decided by other means. The possibility of transitional forms between the series was clearly recognized (e.g. 1952, p. 565). Under the stimulus of a visit by Dr. Tuttle to Cambridge in 1951 it was decided to investigate the anomalous properties of the Madagascar felspars in relation to their iron content and further to test the effect of iron on the d ($\bar{2}01$) powder method for the determination of the compositions of alkali-felspars

(Bowen and Tuttle, 1950). At first it seemed likely that there is a direct relationship between optic axial angle (and orientation) and iron content. However, after detailed study of sixteen crystals from the one locality it now appears that specimens with the optic axial plane parallel to (010) are in fact to be regarded as high-temperature modifications approximating to Tuttle's 'high-temperature sanidine' series. These presumably have a largely disordered arrangement of the Si and Al atoms (cf. Barth, 1934; Cole, Sörum, and Kennard, 1949; Laves, 1952). A transition tending towards common orthoclase is recognized on the basis of intermediate optic axial angles and lattice dimensions. The effect of iron seems to be to promote the stability of the sanidine modification. Some remarks are made in an appendix on the excellent *d* $(\bar{2}01)$ method for the determination of the composition of alkali-felspars.

PREVIOUS WORK.

Yellow orthoclase of gem quality from Itrongay, near Fianarantsoa, Madagascar, was first described by Lacroix (1912), who states that the crystals come from a miarolitic pegmatite which also contains quartz, transparent diopside, adularia, apatite, chalcedony, and opal. Outcrops of the pegmatite are small, but its constituents are abundant on the surface as crystals and broken fragments in part enclosed in a calcareous tufa of recent formation. Lacroix observed that the density and other properties were variable, and when in 1913 he published an analysis showing 2·88 % Fe_2O_3, he suggested that ferric iron replaces equivalent amounts of aluminium within the structure. This suggestion has met with general acceptance. In 1922 Lacroix commented on the similarity to sanidine in optic orientation, but he contended that, unlike sanidine, the Madagascar orthoclase is a pegmatite mineral of relatively low-temperature formation.

Owing no doubt to the high quality of the Itrongay crystals, at least nine analyses of them have been published from time to time and specimens have been used by numerous workers in experiments on the properties of felspars. Following the observations of Kôzu (1916), a series of three analyses made by Seto (1923) showed a relation between depth of colour, iron content, and refractive indices. Kôzu and Saiki (1925) investigated the thermal expansion of the mineral, and Kôzu and Suzuki (1925), Barth (1931), and Spencer (1930, 1937) have all used specimens in experiments on the influence of heat on the optic axial angle. Lacroix himself (1912) observed that the yellow colour is unchanged on prolonged heating at red-heat. Powders have been X-rayed by Ito and Inuzuka (1936), and by Osten (1951), and the approximate cell size of Spencer's specimen 'A' was determined by Chao, Smare, and Taylor (1939). Six existing analyses were brought together by Faust (1936), who carried out a study of the melting relations of pure synthetic iron-orthoclase. Various other writers, such as Alling (1923) and Rosenquist (1951), have commented on the Itrongay felspars in the course of discussions on the entry of iron into the felspar structure.

MATERIAL.

The material available for study consisted of six crystals from the museum of the Department of Mineralogy and Petrology, Cambridge; two provided by Mr. B. W. Anderson of the gemmological laboratory of the London Chamber of Commerce; and a fine collection of about a dozen crystals provided by Professor M. Roques of Clermont-Ferrand. In addition, small fragments of Spencer's specimen 'A' were used for X-ray powder photographs. All the crystals studied are broken fragments, but no. 1 shows a combination of the forms $\{010\}$, $\{110\}$, $\{130\}$, and $\{20\bar{1}\}$. In each case there is a particularly conspicuous basal cleavage, and a less perfect cleavage parallel to (010). The colour varies from very pale yellow to deep amber-yellow and is clearly related to the iron content. With one exception all the crystals studied in detail are perfectly clear and transparent and appear to consist of one phase only. The exception, no. 14, shows a pearly schiller due to cryptoperthitic lamellae subparallel to (100) and it is also interesting on account of the presence of fluid-and-bubble inclusions in the form of negative crystals.

CHEMICAL COMPOSITION.

Three analyses from the literature that are accompanied by optical data are reproduced in table I together with two new analyses by Mr. J. H. Scoon. In each case compositions are recalculated to weight per cent. of the components orthoclase, iron-orthoclase ($KFeSi_3O_8$), albite, and anorthite. Following Faust (1936), small amounts of FeO are treated as Fe_2O_3. Ferric iron can be accounted for in the felspar structure more easily than can ferrous, since in so many minerals Fe^{+3} (ionic radius 0·67 Å.) readily replaces Al^{+3} (0·57 Å.). Some further slight justification for the course here followed comes from the fact that the small amounts of FeO reported in some analyses are at most not much greater than the blank likely to be encountered in a normal FeO

TABLE I. Analyses and optical properties of ferriferous Madagascar alkali-felspars.

	2.	6.	A.	S1.	S2.
SiO_2	64·94	64·76	64·40	64·25	64·21
TiO_2	nil	nil	—	—	—
Al_2O_3	16·74	17·22	18·70	16·06	17·78
Fe_2O_3	2·56	1·50	0·62	2·93	1·15
FeO	nil	nil	0·09	0·25	0·09
MnO	nil	nil	—	—	—
MgO	0·04	0·04	trace	nil	nil
CaO	0·03	0·06	trace	trace	0·07
Na_2O	0·79	0·47	0·46	0·44	0·42
K_2O	15·33	16·00	16·14	16·15	15·21
H_2O-	nil	nil	—	—	—
	100·43	100·05	100·41	100·08	'99·63'
Recalculated composition, weight per cent.					
Or	83·3	89·9	93·3	84·0	90·7
Fe-Or	9·8	5·8	2·8	12·3	5·1
Ab	6·8	4·0	3·9	3·7	3·8
An	0·1	0·3	—	trace	0·4
Optical properties (Na_D light).					
α	1·5265	1·522	1·5194	1·5216	1·5185
β	1·531	1·5265	1·5237	1·5259	1·5225
γ	1·5315	1·5265	1·5241	1·5261	1·5239
$2V_\alpha$ (observed range) ...	32–33½°	11½–17°	—	—	—
$2V_\alpha$ (average)	32½°	13½°	34·8°	20° 17′	—
Optic axial plane ...	$\parallel(010)$	$\perp(010)$	$\perp(010)$	$\parallel(010)$	—
Dispersion	$v > r$	$r > v$	$r > v$	$v > r$	—
$\alpha{:}a$ in obtuse angle β ...	5°	5½°	5·2°	—	—
After treatment at 1075° C.					
$2V_\alpha$	55°	55–56°	53·8°	—	—
Optic axial plane ...	$\parallel(010)$	$\parallel(010)$	$\parallel(010)$	—	—
Dispersion	$v > r$	$v > r$	$v > r$	—	—

2. Amber-yellow crystal. New analysis by J. H. Scoon.
6. Pale yellow crystal. New analysis by J. H. Scoon.
A. Spencer 'A', 1937. E. Spencer, anal.
S1. Kôzu, 1916; Seto, 1923. K. Seto, anal.
S2. Lighter colour than S1. Seto, 1923. K. Seto, anal.

determination. Mr. Scoon reports that no appreciable amounts of FeO are present in the two specimens analysed by him. The fact that Fe^{+3} does actually replace Al^{+3} in the felspar structure was adequately demonstrated by Faust and is supported by atomic formulae calculated from the new analyses thus:

no. 2, $(K_{0\cdot90}Na_{0\cdot07})(Al_{0\cdot91}Fe_{0\cdot09})Si_{3\cdot01}O_8$,
no. 6, $(K_{0\cdot95}Na_{0\cdot04})(Al_{0\cdot94}Fe_{0\cdot05})Si_{3\cdot01}O_8$.

Partial analyses for iron (table II) have been carried out on thirteen crystals, three of them by Mr. Scoon using the thioglycollic acid colorimetric method, and the remainder by the writer using a method involving reduction and titration, supported in many cases by separate colorimetric estimations. The plagioclase component has been estimated by X-ray methods as described later.

TABLE II. Partial analyses of yellow Madagascar orthoclases and optical properties.

	1.	3.	4.	5.	7.	9.	10.
Fe_2O_3 %	2·0	1·45	0·9	n.d.	1·25	3·25*	2·60*
$KFeSi_3O_8$ weight %	7·7	5·6	3·5	n.d.	4·8	12·5	10·0
(Ab+An) % by $d(\bar{2}01)$	4	6	4	0	2	0	1
Refractive indices α	1·5245	1·523	1·521	1·521	1·522	1·5285	1·526
β	1·529	1·5275	1·5255	1·5255	1·5265	1·532	1·530
γ	1·5295	1·5277	1·526	1·5255	1·5265	1·533	1·531
$2V_\alpha$ observed range	25½–39°	12½–23½°	33–35½°	12½–22°	3–22°	49–51°	44–48°
$2V_\alpha$ average	28°	18°	35°	17°	13°	50°	45½°
Optic axial plane	$\parallel$(010)	$\perp$(010)	$\perp$(010)	$\perp$(010)	$\parallel$(010)	$\parallel$(010)	$\parallel$(010)
Dispersion	$v > r$	$r > v$	$r > v$	$r > v$	$v > r$	$v > r$	$v > r$

Properties after heating at 1075° C. for 160 hours.

	1.	3.	4.	5.	7.	9.	10.
$2V_\alpha$	—	—	—	—	—	60½°	—
Optic axial plane	—	—	—	—	—	$\parallel$(010)	—
Dispersion	—	—	—	—	—	$v > r$	—

	11.	12.	13.	14.	15.	16.
Fe_2O_3 %	1·52*	1·4	0·5	1·5	1·7	0·5
$KFeSi_3O_8$ weight %	5·9	5·4	1·9	5·8	6·6	1·9
(Ab+An) % by $d(\bar{2}01)$	3	1	3	9†	7	4
Refractive indices α	1·5225	1·5225	1·520	1·5235	1·5235	1·520
β	1·5265	1·5265	1·5235	1·5275	1·5275	1·524
γ	1·527	1·527	1·524	1·528	1·528	1·5245
$2V_\alpha$ observed range	22–31°	22–33°	34–35°	21½–24½°	23½–25½°	34½–36°
$2V_\alpha$ average	26°	25°	34½°	23°	24½°	35½°
Optic axial plane	$\parallel$(010)	$\parallel$(010)	$\perp$(010)	$\perp$(010)	$\perp$(010)	$\perp$(010)
Dispersion	$v > r$	$v > r$	$r > v$	$r > v$	$r > v$	$r > v$

Properties after heating at 1075° C. for 160 hours.

	11.	12.	13.	14.	15.	16.
$2V_\alpha$	50½–54½°	—	—	51°	51°	—
Optic axial plane	$\parallel$(010)	—	—	$\parallel$(010)	$\parallel$(010)	—
Dispersion	$v > r$	—	—	$v > r$	$v > r$	—

Extinction angle $\alpha : a$ in obtuse angle $\beta = 5\frac{1}{2}° \pm \frac{1}{2}°$ in each case.

* J. H. Scoon, analyst.

† Cryptoperthitic $(Ab+An)_5$ for orthoclase component before homogenization.

REFRACTIVE INDICES.

Refractive indices for the newly analysed crystals and for Spencer 'A' are plotted in fig. 1 and the dependence of the indices on the iron content is immediately apparent. In a few cases the indices in different parts of the one crystal were found to vary by amounts up to 0·003 and in such cases mean figures are quoted. As the combined content of albite and anorthite is shown by chemical analysis and by powder photographs to be rather uniformly low, variations in indices from this factor should be correspondingly slight. From the refractive index graphs of Tuttle

(1952, fig. 2) it can be seen that an albite content of 9 %, the highest observed in the Madagascar collection, would raise the indices by about 0·001 relative to albite-free members. An increase of refractive index with iron content is of course to be expected, and Gaubert (1926) has given the figures α 1·601, γ 1·609 for the synthetic iron-orthoclase prepared by Hautefeuille and Perrey (1888).

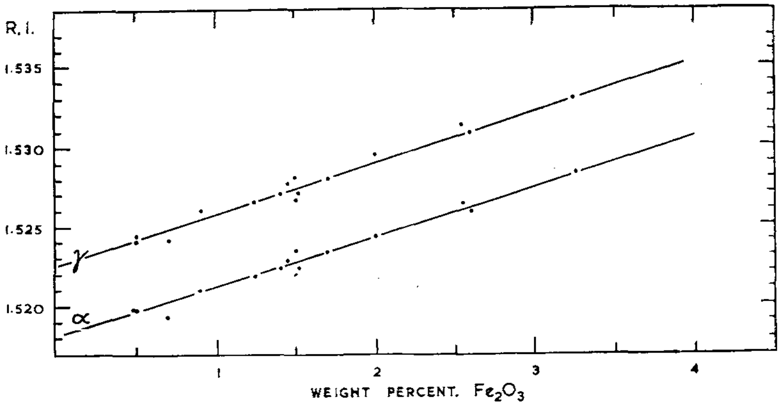

Fig. 1. Refractive indices of ferriferous orthoclase.

Heat-treatment.

Spencer (1937) found that on prolonged heating at 1075° C., the optic axial plane of his specimen 'A' was brought into (010) with 2V 53·8°. Constancy was reached in a little over one hundred hours. At 1120° C. the angle attained was found to be 58°. These properties for the heated natural felspar are those of 'high-temperature sanidine' (Tuttle, 1952). By heating specimens for shorter periods at lower temperatures, Kôzu and Suzuki (1925) and Barth (1931) were able to produce rather smaller changes.

After 2V had been determined on oriented plates of six of the crystals used in the present study, parts were detached and were heated for 160 hours at 1075°±10° C. In each case the optic axial plane after treatment was found to be parallel to (010) with 2V 50–60° (tables I and II). Two specimens, nos. 2 and 6, were given a preliminary heating for 110 hours at 1050–1060°. No. 2 had already reached a value of 55°, but no. 6 had an optic angle of only 45–48°, which increased during subsequent heating to 55–56°.

OPTIC AXIAL ANGLE.

Plates $\frac{1}{2}$–1 mm. thick were cut through each crystal in a direction approximately at right angles to the acute bisectrix. The optic axial angle was measured over this surface on the universal stage, using interference figures to locate the optic axial points with a precision of $\pm\frac{1}{4}$–$\frac{1}{2}$° (tables I, II, fig. 2). The measured angles were found to be variable, in one case over as much as 19°. In some cases the variation could conceivably be due to zoning, but in nos. 5 and 7 especially, 2V varies across the section in a curious blotchy manner quite incompatible with compositional zoning. In order to minimize the effects of any variation in composition that might occur, the analysed samples were taken from material adjacent to that studied optically.

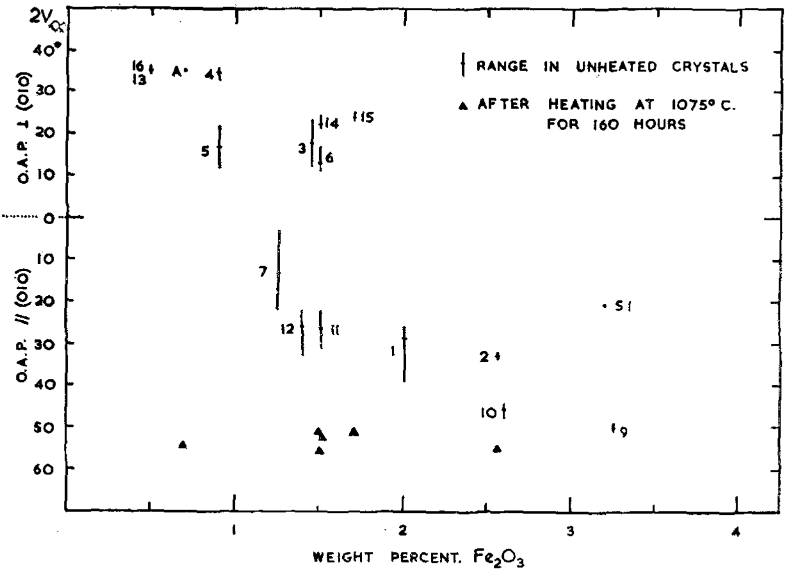

FIG. 2. Optic axial angle plotted against iron content for ferriferous orthoclase from Madagascar.

Strong dispersion of the optic axes is evident in the interference figures of the iron-rich members (cf. Kôzu, 1916) and the dispersion scheme $v > r$ when the optic axial plane is parallel to (010) and $r > v$ when it is perpendicular to (010), provides a check on the optic orientation as determined by other means.

A glance at fig. 2 shows that there is a tendency for the crystals with highest iron content to have their optic axial plane parallel to (010), and in fact this is the case for all five crystals with not less than 2 % Fe_2O_3 (7·7 % $KFeSi_3O_8$). At first it appeared that the iron content directly controls 2V and the optic orientation, but when more crystals became

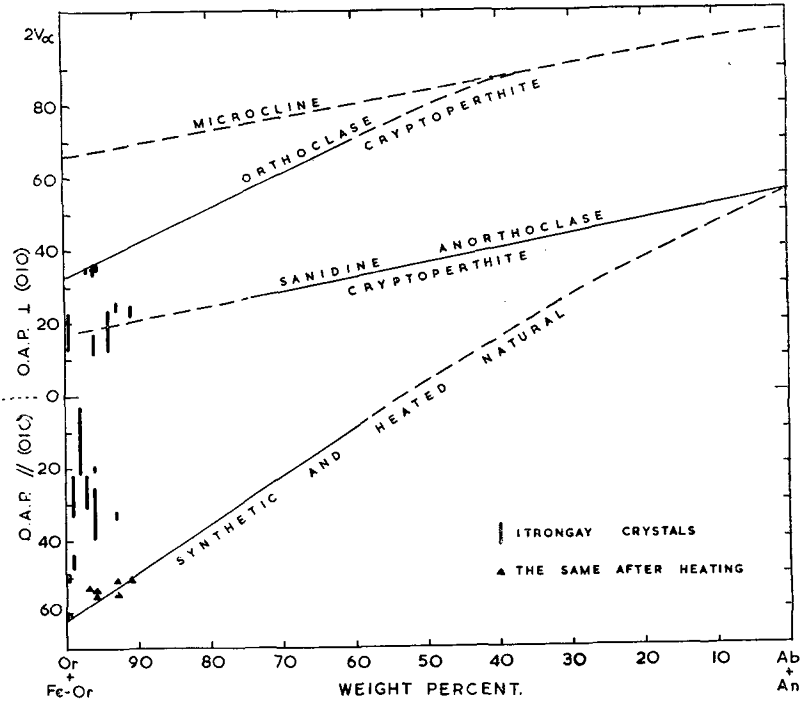

FIG. 3. Graph showing relation between 2V and composition of several series of alkali-felspars (after Tuttle, 1952, fig. 1). Tuttle stresses that the range of values for 2V for natural felspars, as shown in his original diagram, precludes the use of the graph for determination of composition. Data are added for the ferriferous felspars of Itrongay to show the range of intermediate values observed.

available for study, this simple hypothesis became untenable for the following reasons:

(i) Irregular variation in 2V occurs in single crystals, through as much as 19° as already noted.

(ii) Separate crystals with essentially the same chemical composition sometimes vary between themselves in even greater amount. Thus the group 3, 6, 11, and 12, all with approximately 1·5 % Fe_2O_3 and closely comparable refractive indices and albite contents, have optic axial angles reaching 23½° perpendicular to (010) and 33° parallel to (010). There is in effect a difference here of 56½° in the optic axial angle of material of similar composition.

For these reasons it appears that any control that iron content exerts on 2V is imperfect and probably indirect. Furthermore, in the case of the heat-treated material the effect of iron is clearly shown to be small and when the small albite contents are considered the determinations of 2V are found to fall very close to the curves for sanidinized alkali-felspars given by Spencer (1937, fig. 2) and Tuttle (1952, fig. 1), as shown in fig. 3.

Irrespective of iron content, an almost continuous series of values has been observed for the unheated crystals, the actual range noted being 2V 3–51° with the optic axial plane parallel to (010), and 2V 11½–25½°, 33–36° when it is perpendicular to (010).

Correlation between lattice spacings and optic axial angle.

During the inspection of powder photographs of Itrongay felspars it became evident that heat-treatment produces conspicuous changes in the region of the two strong lines that occur close together in the region of 3·2 to 3·3 Å. In unheated material such as Spencer 'A' they consist of an unresolved doublet 002, 040 and another doublet $\bar{2}02$, 220 which is usually resolved in good quality photographs taken on a 19-cm. camera with copper radiation, and which is very clearly resolved on an X-ray spectrometer chart demonstrated to the writer by Dr. W. S. MacKenzie. Upon heat-treatment, the strongest components 002, 220 move farther apart, $\bar{2}02$ is clearly visible between them, and 040 less readily so. Systematic changes in positions of certain other reflections can also be traced. Cole, Sörum, and Kennard (1949, p. 282) showed that on sanidinization of the orthoclase Spencer 'C', the *c*-axis was reduced in length, whereas *b* increased and *a* underwent little change. Furthermore, they pointed out (p. 287) that the changes are in the direction to be expected if sanidinization is due to a disordering process of Al atoms from Si_1 to Si_1 and Si_2 positions. It follows from the cell dimensions given that sanidinization must result in an increase in the angular separation of the 002 and 220 reflections in powder diagrams. Thus for Cu-$K\alpha$ radiation, $2\theta_{(002)}-2\theta_{(220)}$ (calculated) = 0·66° for unheated Spencer 'C', increasing to 0·76° for the heated material. This corresponds to the observed behaviour of the Itrongay felspars.

Now if the ferriferous felspars with small optic axial angles represent intermediate stages in a transition from 'high-temperature sanidine' with 2V 50–60° parallel to (010), to common orthoclase which for the moment we can consider as having 2V 35° perpendicular to (010), then one might expect that their lattice dimensions would also have intermediate values. With an ordinary powder camera the angular separation of adjacent lines can often be measured with greater accuracy than can the absolute value of 2θ. As the differences in lattice dimensions involved in the present problem are small, it is convenient to study them by means of such angular separations of adjacent lines, and since *c* decreases on sanidinization whereas *b* increases, the differential movement of pairs such as 002, 040 should be specially suitable for investigation. These particular reflections are not sufficiently well resolved, however, to allow their study, so data are presented in table III and fig. 4*a*, *c* for

TABLE III. $\Delta 2\theta$ values for ferriferous orthoclase from Itrongay, Madagascar, and for synthetic $KAlSi_3O_8$. (Cu-$K\alpha$ radiation, 19-cm.-diameter powder camera.)

$\Delta 2\theta_1$: $2\theta_{(040,002)}-2\theta_{(220)}$ or $2\theta_{(002)}-2\theta_{(220)}$.

$\Delta 2\theta_{1a}$: The same adjusted towards zero plagioclase content.

$\Delta 2\theta_2$: $2\theta_{(11\bar{2})}-2\theta_{(130)}$.

A. *Unheated:*

Specimen	(Ab+An).*	Op. ax. pl.	$2V_\alpha$ (av.)	$\Delta 2\theta_1$.	$\Delta 2\theta_{1a}$.	$\Delta 2\theta_2$.
1	4	∥(010)	28°	0·71°	0·75°	2·175°
2	5	∥(010)	32½	0·68	0·73	2·14
3	6	⊥(010)	18	0·65	0·71	2·12
4	4	⊥(010)	35	0·65	0·69	2·12
5	0	⊥(010)	17	0·68	0·68	2·15
6	1	⊥(010)	13½	0·71	0·72	2·155
7	2	∥(010)	13	0·73	0·75	2·18
9	0	∥(010)	50	0·77	0·77	2·17
10	1	∥(010)	45½	0·745	0·755	2·16
11	3	∥(010)	26	0·72	0·75	2·185
12	1	∥(010)	25	0·73	0·74	2·17
13	3	⊥(010)	34½	0·675	0·705	2·14
14	5	⊥(010)	23	0·645	0·695	2·115
15	7	⊥(010)	24½	0·62	0·69	2·115
16	4	⊥(010)	35½	0·67	0·71	2·125
Spencer 'A' ...	4	⊥(010)	34·8	0·635	0·675	2·115
B. *Heated 160 hours at 1075° C., and synthetic:*						
9	0	∥(010)	60½°	0·85°	0·85°	2·295°
11	3	∥(010)	52½	0·83	0·86	2·26
14	9	∥(010)	51	0·80	0·89	2·24
15	7	∥(010)	51	0·77	0·84	2·245
Spencer 'A' ...	4	∥(010)	53·8	0·82	0·86	2·29
$KAlSi_3O_8$† ...	0	∥(010)	60	0·87	0·87	2·28

* (Ab+An) estimated by *d* ($\bar{2}01$) method.

† X-ray data from Donnay and Donnay (1952, p. 124).

$2\theta_{(11\bar{2})}-2\theta_{(130)}$ and for the separation of the two conspicuous strong lines referred to above. In the latter case, interpretation is complicated by the imperfect resolution of the constituent doublets, but in general the angles refer to $2\theta_{(002,040)}-2\theta_{(220)}$ in the case of unheated specimens and to $2\theta_{(002)}-2\theta_{(220)}$ for heat-treated and synthetic material. The angular separation of these strong lines has been shown by Osten (1951) to vary with albite content. The data of Donnay and Donnay (1952, pp. 124, 125) indicate that $2\theta_{(002)}-2\theta_{(220)}$ for synthetic monoclinic alkali-felspars decreases at the rate of approximately 0·01° for every 1 % albite. In an attempt to adjust the present measurements towards a constant, albite-free basis (fig. 4*b*), $2\theta_{(002)}-2\theta_{(220)}$ (or $2\theta_{(002,040)}-2\theta_{(220)}$) has therefore been reduced by 0·01° for every 1 % (Ab+An) as estimated by the powder method. Data for synthetic $KAlSi_3O_8$ are added for comparison.

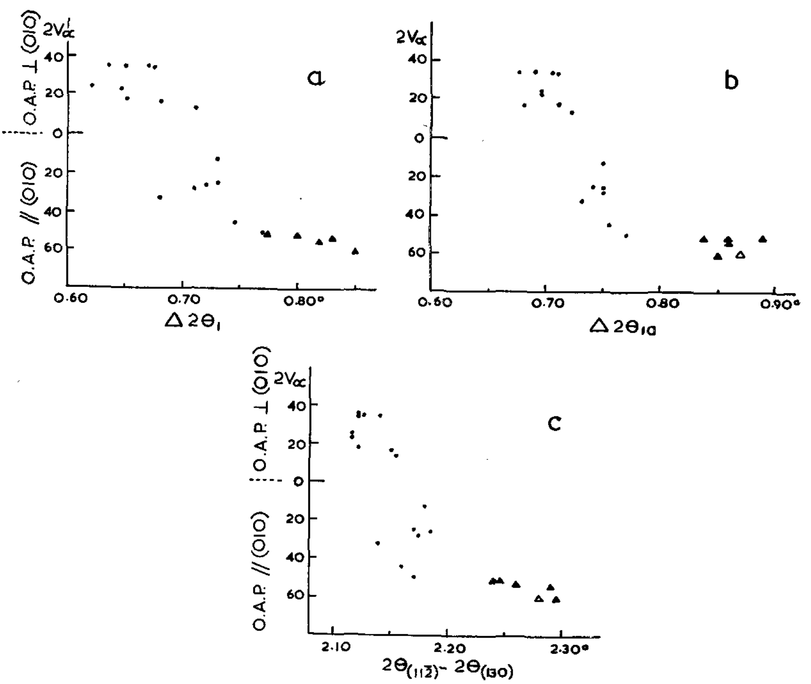

FIG. 4. $\Delta 2\theta$ for pairs of powder lines of alkali-felspars as a function of 2V (see table III). *Points*: Ferriferous orthoclase, Itrongay, Madagascar. *Solid triangles*: The same after heating to 1075° C. for 160 hours. *Open triangles*: Synthetic $KAlSi_3O_8$. Cu-$K\alpha$ radiation.

By averaging repeated measurements of peak positions made with a travelling microscope and vernier, reproducibility of about 0·01° in $\Delta 2\theta$ has been attained. In spite of a scatter of points that is rather too great to be ascribed to simple errors of measurement alone, fig. 4 shows that there is a strong correlation between optic axial angle and lattice spacings. As a group, the Itrongay crystals with high-temperature sanidine orientation are seen to be intermediate between those with orthoclase orientation and the heat-treated or synthetic specimens. This is taken as evidence that the anomalous optical properties, such as those recorded by Kôzu (1916), are due to the occurrence of forms transitional between high-temperature sanidine (disordered) and common orthoclase (presumed to be partially ordered). In detail it is seen that the lattice spacings of the transitional specimens tend to be nearer to those corresponding to common orthoclase than to those of the heat-treated or synthetic crystals even where 2V most closely approaches the condition of the latter.

The general conclusions of this section are supported by the consideration of cell dimensions (table IV) calculated from the powder patterns of three typical Itrongay specimens, chosen for their wide range of 2V yet closely comparable chemical compositions. In the critical *b* and *c* dimensions no. 11 (unheated) is seen to be intermediate between no. 4 and no. 11 (heat-treated), as it is also in 2V. Data for Spencer 'C' are added for comparison. A close similarity in behaviour is evident, the only significant difference being that the higher albite content of 'C', 9 % as against an estimated 3 to 4 % in nos. 4 and 11, is reflected in a smaller *a*-axis. The powder data used for the computation of these cell dimensions are given in table V.

TABLE IV. Cell dimensions and 2V of ferriferous felspars and of Spencer 'C'.

	4.	11.	11 (heat-treated).	C.*	C* (heat-treated).
a (Å.) ...	$8{\cdot}58_1$	$8{\cdot}58_6$	$8{\cdot}59_6$	$8{\cdot}561_6$	$8{\cdot}564_2$
b	$12{\cdot}99_0$	$13{\cdot}02_0$	$13{\cdot}03_3$	$12{\cdot}996_2$	$13{\cdot}030_0$
c	$7{\cdot}20_0$	$7{\cdot}18_9$	$7{\cdot}17_9$	$7{\cdot}193_4$	$7{\cdot}174_9$
β	$116{\cdot}0_6^\circ$	$115{\cdot}9_8^\circ$	$116{\cdot}0_3^\circ$	$116{\cdot}01_5^\circ$	$115{\cdot}99_4^\circ$
Op. ax. pl. ...	$\perp(010)$	$\parallel(010)$	$\parallel(010)$	$\perp(010)$	$\parallel(010)$
$2V_\alpha$	35°	26°	$52\frac{1}{2}^\circ$	43·6°	44·8°

* X-ray data from Cole, Sörum, and Kennard, 1949, p. 282; optical data from Spencer, 1937, plate XVIII.

TABLE V. Powder data used in the calculation of cell dimensions (see table IV). Cu-$K\alpha$ radiation, Ni filter.

hkl.	Int.	4.	11.	11 heat-treated.
$\bar{2}01$	4	θ = 10·513°	θ = 10·504°	θ = 10·503°
111	2½	11·275	11·265	11·277
130	7	11·781	11·760	11·746
$13\bar{1}$	2	12·307	12·303	12·283
$11\bar{2}$	3	12·840	12·852	12·876
220	7	13·444	13·421	13·413
$20\bar{2}$	4	—	(13·56)	(13·57)
040	3	13·769	13·781	(13·70)
002	10			13·828
131	5	14·928	14·904	14·907
$13\bar{2}$	1	(16·17)	(16·165)	(16·18)
$31\bar{2}$	< 1	—	(17·205)	—
$24\bar{1}$	2	17·421	17·394	17·375
112	< 1	—	(17·60)	—
060	3	(20·87)	(20·83)	(20·785)

Angles for inferior reflections in brackets.
The unresolved doublet 041, 022 (~ 15·4°) and several weaker lines are omitted.
Limits of error approximately 0·01° in θ.

CONCLUDING DISCUSSION.

It has been shown that the variations in 2V and optical orientation of the ferriferous felspars cannot be related directly to the chemical composition, but that both the observed optical data and lattice spacings are compatible with the existence of high-temperature sanidine modifications and transitional forms tending towards common orthoclase. The occurrence of these felspars in a pegmatite is significant in view of the belief sometimes expressed that high-temperature felspars are absent among plutonic associations. A sanidine-bearing pegmatite emplaced in rhyolite-porphyry at shallow depth has also been reported recently (Kelley and Branson, 1947).

A tendency for the most ferriferous felspars (e.g. 1, 2, 9, 10, S1) to have their optic axial planes parallel to (010) has already been noted. Two main hypotheses could be proposed to explain this.

(i) The most iron-rich crystals crystallized as a high-temperature modification, whereas the others crystallized as a low-temperature modification, perhaps, but not necessarily, at a lower temperature. This view makes no allowance for transitional forms and is inadequate.

(ii) All the crystals formed in the high-temperature sanidine condition or in a form approximating to this, and they tended to change over towards common orthoclase. The existence of highly irregular variations in 2V within the one crystal supports the reality of some uncompleted process of this type. Such a mechanism would be consistent with the view expressed by Laves (1952) that there are two stable modifications of potash-felspar, sanidine stable at high temperatures and microcline stable at low temperatures, and that the former tends to pass towards the latter by an ordering process, with common orthoclase as an unstable intermediate stage.

If the second hypothesis is accepted it follows that a high iron content has tended to inhibit the ordering process. This appears to be a reasonable assumption when it is remembered that the Fe^{+3} ion is larger than Al^{+3}, which it replaces. When the larger Fe^{+3} ions are distributed at random through disordered $AlSi_3$ positions, they might be expected to exert less of a disturbing influence on the felspar structure than if they were concentrated into a restricted number of Al positions as in a fully ordered arrangement. In some interesting experiments using radioactive tracers, Rosenquist (1951) found that up to 0·21 % Fe_2O_3 could enter powdered microcline at 980° C. and much smaller quantities were taken up at lower temperatures. The fact that microcline normally does not carry large amounts of iron in solid solution, although microcline-perthites frequently contain oriented and presumably exsolved lamellae of haematite (Andersen, 1915), indicates the possibility that the ordered structure may be incapable of holding much iron. If so, the presence of iron in a sanidine should have the effect of retarding the ordering process. If ordering is to proceed to the microcline stage (not seen in the Itrongay series) it may be that most of the iron must first be expelled from the lattice. The precise mechanism by which haematite can separate from $KFeSi_3O_8$-bearing felspar remains obscure, and the suggestion by Rosenquist (1951) of complementary introduction of Al_2O_3 poses its own problems. An apparent exception to the above generalization must be recorded. The Palabora microcline, described by Shand (1931, p. 92), contains the relatively large amount of 1·02 % Fe_2O_3.

It remains to consider the question of terminology. Those members with the optic axial plane parallel to (010) are adequately described as sanidine (or high-temperature sanidine). Several crystals have $2V \sim 35°$ and fall near the soda-poor end of the orthoclase curve (fig. 3). However, the only 'orthoclase' with 2V less than 40° available to Spencer (1937) and Tuttle (1952) when they drew up this curve was the ferriferous Spencer 'A' from Madagascar. It is now shown to be associated in its occurrence with sanidines that show more or less continuously variable properties. Hence whether or not Spencer 'A' can be considered as specifically representative of 'orthoclase' is largely a matter of arbitrary definition, unless it can be shown that the two small gaps in observed 2V are due to causes other than incomplete sampling.

APPENDIX: NOTES ON THE X-RAY-POWDER METHOD FOR THE DETERMINATION OF ALKALI-FELSPARS.

Bowen and Tuttle (1950, p. 491) have shown that the measurement of lattice spacings by X-rays, in particular the measurement of *d* ($\bar{2}01$), affords a very accurate and convenient method for the determination of the composition of synthetic soda-potash-felspars. For the present work the procedure used in the Department of Mineralogy and Petrology, Cambridge, was followed, and synthetic spinel, $MgO.Al_2O_3$ ($a = 8{\cdot}081$ Å., $d\ (111) = 4{\cdot}665$ Å.) was mixed with each felspar to be determined by the powder method in the proportions of 1 part powdered spinel to about 4 or 5 parts felspar. The 111 (spinel) reflection then provides a conveniently placed internal standard line. To avoid the necessity of calculating *d* ($\bar{2}01$) for each felspar, it is easy to construct for any camera and wave-length a graph from which the composition Or/(Ab+An) can be read off directly from the linear distance on the film between the 111 (spinel) and $\bar{2}01$ (felspar) reflections. Using a 19-cm.-diameter powder camera, filtered Cu-$K\alpha$ radiation, and a low-power travelling microscope, it is possible to measure this distance on good-quality photographs with a precision corresponding to an error of ± 2 % (Ab+An) in the composition. Occasionally it may be necessary to correct for film shrinkage, but errors due to this are usually negligible in the small distance to be measured.

The theoretical basis for the *d* ($\bar{2}01$) method lies in the fact that the lengths of the *a*- and *c*-axes and the angle β all vary in continuous fashion through the series $KAlSi_3O_8$–$NaAlSi_3O_8$ (Donnay and Donnay, 1952, fig. 6; Laves, 1952, fig. 4). The most marked change is a reduction in the length of *a*. Laves points out that *d* ($\bar{2}01$) does not depend on the interaxial angles α and γ, and largely for this reason the method is applicable not only to monoclinic felspars but also to triclinic felspars such as anorthoclase. Analysed microclines from Michigan (Klein, 1939) and, after homogenization, Coul More, Loch Assynt (Peach et al., 1907, p. 448) have also been observed by the writer to have $\bar{2}01$ spacings compatible with Bowen and Tuttle's graph (1950, fig. 2).

This determinative graph was constructed for synthetic felspars, in effect 'high-temperature sanidines'. Cole, Sörum, and Kennard (1949) have determined the cell constants for the orthoclase Spencer 'C' and its sanidinized modification with great precision. Although sanidinization produces significant changes in cell dimensions, the net effect on *d* ($\bar{2}01$) is slight compared with those changes that accompany varying albite content. Thus it can be calculated that *d* ($\bar{2}01$) for Spencer 'C' is $4{\cdot}217_3$ and for its sanidinized modification $4{\cdot}217_0$, the difference being negligible and the spacing appropriate for such a felspar containing 9 % (Ab+An). Further confirmation that the Bowen–Tuttle graph may be used to determine the composition of potash-rich low-temperature orthoclase phases in addition to high-temperature synthetic alkali-felspars comes from appropriate and virtually identical direct measurements, before and after heat-treatment, of *d* ($\bar{2}01$), for Spencer 'C', for the ferriferous Madagascar orthoclases, and for the St. Gotthard adularia Spencer 'B' $(Ab+An)_9$. It may be noted, however, that the *d* ($\bar{2}01$) curves for high- and low-temperature felspars diverge slightly at the soda-rich end. Thus albite from Amelia, Virginia, with 2·6 % Or, gave the result 4·030 Å., and after inversion to high-temperature albite a distinctly greater spacing, 4·037 Å. Two potash-free authigenic albites from Bellefonte, Pennsylvania (Honess and Jeffries, 1940), and albite from Alp Rischuna, Switzerland (Lewis, 1915), have spacings 4·027–4·029 Å., whereas synthetic high-temperature albite gave 4·034 Å. These variations are near the limit of sensitivity of the methods employed but appear to be significant, high-temperature albite having the greater spacing.

This valuable technique must not be applied without due care. Laves (1952, p. 562) found by single-crystal photographs of certain cryptoperthites that the cell dimensions of the components did not accord with the values found for homogeneous felspars; thus the length of the *a*-axis of the sodic component of one example indicated the impossible composition of Ab_{110}. Similarly, *d* ($\bar{2}01$) values determined by the present writer from the powder patterns of the cryptoperthitic moonstones I, J, K, and M described by Spencer (1937) give impossible values of up to 110 % Ab and Or for the sodic and potassic phases respectively. Thus in the case of the homogeneous low-temperature potash-rich felspars examined by the writer, including orthoclase, adularia, and microclines, the Bowen–Tuttle curve gives reliable estimates of composition. The results for the finer orthoclase cryptoperthites, however, do not always conform, as discussed by Laves.

It is important to consider the effect on *d* ($\bar{2}01$) of components other than orthoclase and albite. It can readily be verified that soda-rich plagioclases have essentially the same $\bar{2}01$ spacings as pure albite and it follows that moderate amounts of the anorthite component have the same effect on d ($\bar{2}01$) as albite. The total albite plus anorthite is determined. It may be recalled that Tuttle and Bowen (1950, p. 578) and Claisse (1950) have both described powder methods for the determination of certain plagioclases. To test the effect of iron, d ($\bar{2}01$) has been measured for the fully analysed ferriferous orthoclases 2, 6, and Spencer 'A', with 2·56 %, 1·50 %, and 0·62 % Fe_2O_3, respectively. The results for the first two, 4·224 Å. and 4·231 Å., are 0·004–0·006 Å. greater than would be expected for iron-free felspars of corresponding soda content. This would correspond to a possible error by underestimation of about 2–3 % (Ab+An) if the effect of iron-orthoclase was ignored. This effect has not been allowed for in the X-ray determinations of (Ab+An) for the Madagascar felspars given in table II. In the case of Spencer 'A' no significant departure from Bowen and Tuttle's graph was observed. As is to be expected from a consideration of ionic radii, the small amounts of iron encountered in normal felspars, generally less than 0·5 % Fe_2O_3, can have only an insignificant effect on determinations by this method.

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