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Transitional optics of some andesines and labradorites.

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I. Introduction.

RECENT optical and structural investigations have shown that both high- and low-temperature forms of plagioclase can exist naturally over the range An_{0-70}, and in the more basic plagioclases (An_{70-90}) Gay (1954) has shown that a structural distinction can be effected although no definite optical differences have yet been established. In the anorthite range slight optical and distinct structural differences have been observed between synthetic plagioclases and crystal lapilli on the one hand and all other natural plagioclases on the other (Gay, 1953).

Nearly all published data on natural high-temperature plagioclases are confined to volcanic rocks and almost without exception published information on plutonic or metamorphic rocks indicates a low-temperature state for the plagioclase. No systematic investigation of the plagioclases from hypabyssal rocks or from the smaller plutonic intrusions appears to have been undertaken; and the current views of most optical workers seem to indicate that plagioclase felspars belong either to the high- or the low-temperature series, and that transitional states, if present at all, are very rare. The only specific records of transitional optics in plagioclases are in the works of Oftedahl (1948) on the andesines of the rhomb-porphyries in the Oslo area and of Tuttle and Keith (1954) for the oligoclase (An_{17}) of the Beinn an Dubhaich granite, Skye.

In this paper all the plagioclases studied are andesines or labradorites and most of them come from the great tholeiitic dolerite sills in which many of the parent rocks are truly gabbroic in texture. All the specimens have been examined optically using a Leitz four-axis universal stage, and refractive index measurements were carried out on four of the specimens selected for analysis. X-ray single-crystal oscillation photographs have also been taken of most of them in their natural state. Selected grains were heat-treated and then examined optically again, and in critical cases a further X-ray examination has been made of the heat-treated crystals.

II. The recognition of high- and low-temperature optics.

Köhler (1941) was the first to note definitely the effect of the thermal history on the optics of plagioclase felspars. He showed that plagioclases occurring as phenocrysts in volcanic rocks had an optical orientation which differed noticeably from that of the 'standard plagioclases' of plutonic rocks or gneisses on which Reinhard (1931) had based his determinative curves. Köhler's investigations covered the composition range An_{35-73}, and as standard high-temperature plagioclases he selected for further optical study fragments from three of the analysed fractions of felspars having compositions 35·5, 45·5, and 54 % An, described by Ernst and Nieland (1934) from the island of Linosa.

In the andesine-labradorite range the distinction between high- and low-temperature forms can best be shown optically by the positions of the (010) or (001) face poles when plotted on a stereogram with fixed optical directions (fig. 1). For plagioclases more sodic than 45 % An the distinction is greater if the positions of the two optic axes A and B are used and plotted on a conventionally oriented stereogram with (001) at the centre and (010) at the right-hand horizontal radius (fig. 2).

The measurements were carried out using white light except for the final setting of the optic axial plane and for this a yellow 589 $\mu\mu$ filter was used to minimize the effect of the pronounced dispersion. In all specimens, except those from Linosa, St. John's Point, and Esterel, at least ten separate twinned crystals were measured using the orthoscopic method. Since large simply-twinned fragments of the Linosa, St. John's Point, and Esterel felspars were available, these were mounted, ground flat on the upper surface, and oriented using the conoscopic method. Because of the pronounced dispersion of the optic axial plane

in plagioclases a conoscopic setting of this plane is not as satisfactory as the orthoscopic setting, but the conoscopic method can detect the positions of the optic axes to $\pm\frac{1}{2}°$ which is a considerable improvement on the accuracy of the conventional orthoscopic method.

A striking feature of all the rocks examined containing plagioclase An_{35-50} was the number of individual crystals (about 5–10 % of the total) elongated parallel to the x crystallographic axis. Sections of such crystals oriented perpendicular to the x-axis are readily recognized in thin section by their square cross-sections and by the presence of the (001) and (010) cleavages. Moreover, in such crystals simple fourlings with re-entrant angles of 8° developed by primary twinning on the albite and Ala-A laws can frequently be observed and such sections are particularly suitable for making accurate optical measurements. Primary twinning of this type on the Ala-A law seems to be associated with plagioclase whose composition centres around An_{40}. Plagioclases more basic than An_{50} were examined carefully to see whether similar fourlings or simple Ala-A twins were developed, but none could be found.

By using twinned fourlings of this type it was possible to locate the position of the x crystallographic axis and the (010) plane very accurately, and, since for all plagioclases the crystallographic β-angle does not deviate by more than $\frac{1}{2}°$ from 116°, [001] can also be located accurately when the optical orientation has been established. In many of these primary twins the sharp albite composition plane proved to be vicinal in nature, being inclined to the true (010) plane by as much as 3°. Such deviations were never observed for twins on (001). All plotted points in the diagrams represent mean angular values measured over twin axes, twin axes being used in all cases as reference directions.

Refractive index measurements of the very few analysed high-temperature and transitional plagioclase felspars available approach very closely to Chayes's curves (1952), and it would appear that any clear distinction in the refractive indices of the high- and low-temperature series of plagioclases can only be effected at compositions approaching pure albite. The only systematic deviation from Chayes's curves that could be noted was a tendency for the refractive indices of high-temperature and transitional plagioclases more sodic than about An_{50} to be about 0·001 lower than the curves (with the exception of pure albite), and for those more basic than An_{50} to be higher by about the same amount. These deviations are within the limits of experimental error and will not be considered further as the data at present are so meagre. It would seem, therefore, that with the exception of very sodic

plagioclases, any estimation of the composition of a natural plagioclase felspar based on accurate refractive index measurements should be satisfactory within $\pm 2\,\%$, irrespective of the structural state of the mineral.

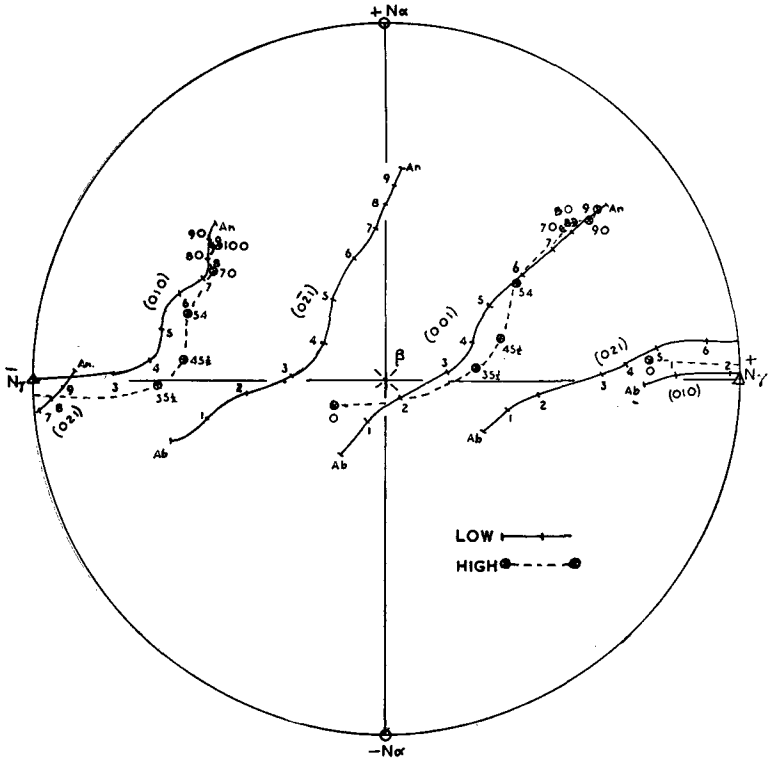

FIG. 1. Fedorov-Nikitin type stereogram showing the migration of crystallographic poles for high- and low-temperature plagioclase felspars with reference to fixed optical vectors. Low-temperature curves of Reinhard (1931); high-temperature curves based on Tuttle and Bowen (1950), Köhler (1941), and Tertsch (1942).

III. THE STRUCTURES OF THE INTERMEDIATE PLAGIOCLASES.

In the low-temperature intermediate plagioclases, An_{30-70}, X-ray reflections which have '$h+k$' even and 'l' odd (indexed on the basis of a 14 Å. c-axis) are doubled. These doubled spots, corresponding to the type 'b' reflections of anorthite described by Gay (1954), are symmetrically disposed about the positions of the odd-layer lines on c-axis

oscillation photographs and symmetrically about all layer lines for *a*- and *b*-axis photographs. Cole, Sörum, and Taylor (1951) showed that the separation of these doubled spots varied in a regular manner and could be correlated with the composition of the felspar. In the low-temperature

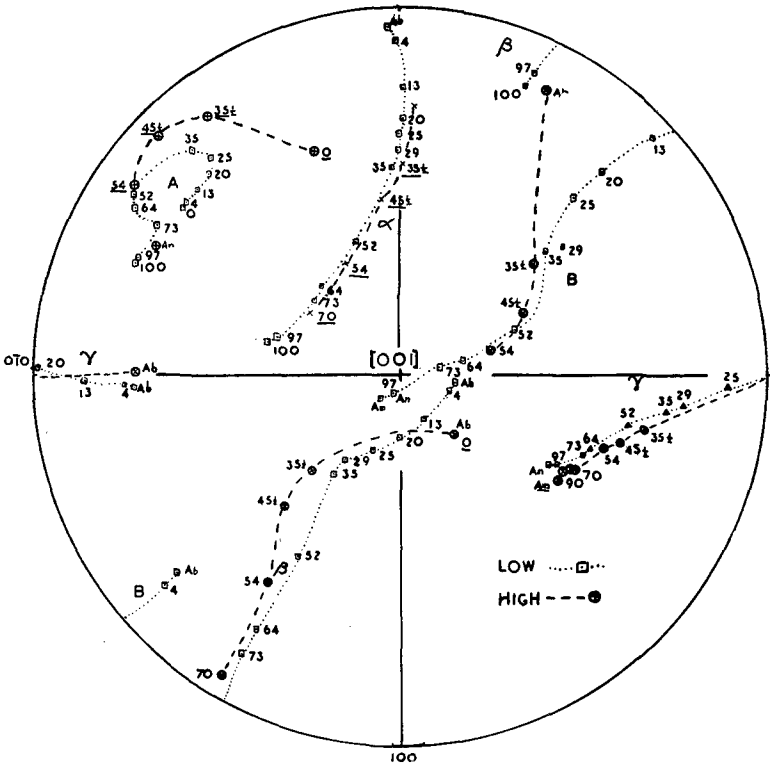

FIG. 2. Stereogram showing the positions of the poles of the principal vibration directions and of the optic axes of high- and low-temperature plagioclase felspars. Low-temperature curves of Reinhard (1931); high-temperature curves based on Tuttle and Bowen (1950), Köhler (1941), and Tertsch (1942).

plagioclases in the range An_{40-55} the subsidiary type '*b*' reflections although weak do not seem to vary noticeably in intensity with change of composition. More recently, Gay (1954) has shown that these weak reflections can be made to disappear by suitable heat-treatment leaving a structure with a 7 Å. *c*-axis, and that in the high-temperature state a 7 Å. *c*-axis type of felspar can exist over the whole range from albite to about An_{90}.

Buerger (1948) and Laves (1952) have suggested that the transformations between high- and low-temperature forms in felspars are order-disorder effects; Gay (1954) considers that this suggestion is in agreement with the nature of the changes observed when basic plagioclases are heated, and that there is little doubt that inversions of this kind exist over the whole of the plagioclase system. He states, further, that by the very nature of the inversion, felspars in transitional states can exist quite stably throughout the series, and has demonstrated their existence for basic plagioclases. In the alkali-felspars, transitional types are now known (Tuttle and Keith, 1954).

IV. Specimens examined.

The specimens to be investigated were selected carefully so that the compositions of the respective plagioclases and pyroxenes in the different doleritic rocks were as similar as possible. In this way it was hoped that any relation between exsolution and inversion in the pyroxenes and the structural state of the plagioclase would become evident. For felspars in the andesine–sodic-labradorite range this has involved a study more particularly of the iron-rich differentiates. The plagioclase from the iron-rich facies of the Beaver Bay diabase has been described in detail, and textural features of the other plagioclases examined have been compared with those noted in this mineral. Mean values for the positions of the optic axes of all felspars examined are given as Becke co-ordinates in table I.

(i) *Andesine from the Beaver Bay diabase, Minnesota.*

This plagioclase comes from a specimen of the relatively coarse-grained iron-rich facies of the great pre-Cambrian Beaver Bay sill-like diabase intrusion (Grout and Schwartz, 1939). The principal associated minerals of the plagioclase are olivine (Fa_{80}), ferroaugite ($Ca_{38}Mg_{28}Fe_{34}$) with extremely fine exsolution lamellae, pigeonite ($Ca_9Mg_{27}Fe_{64}$) much of which has inverted to orthopyroxene, and interstitial primary orthopyroxene (Of_{75}). The pyroxene relations have already been described in detail (Muir, 1954).

The tabular subhedral plagioclase crystals An_{44}, which average about two millimetres in length, are very fresh and virtually unzoned, except at the margins where strong zoning to about An_{20} may occur. Most of the crystals are elongated parallel to the z crystallographic axis, and are flattened on (010), but about ten per cent. of the individuals are elong-

TABLE I. Optical data of plagioclases.

Average values for the positions of optic axes A and B in the projection on (001) of plagioclases (Becke co-ordinates).

Plagioclase.	Composition Wt. % An.	A. λ.	A. φ.	B. λ.	B. φ.	$2V_\gamma$.
Esterel...	40	+80½°	−43°	+35½°	+38°	90°
Beaver Bay	44	+80½	−44½	+30½	+37½	86
New Amalfi EH52...	46½	+80½	−50	+20	+35½	79½
New Amalfi EH20...	50½	+78½	−54	+14	+33	77½
New Amalfi	55	+75	−77	+8	+28	78½
Mount Wellington (summit)	56	+74	−54	+7	+27	81
St. John's Point ...	62	+74	−56	+6½	+25	81
Mount Wellington (875 feet)	68	+68½	−56½	+2	+20½	85½

Albite twins, angles to (010).

	α.	β.	γ.
Esterel	88°	66°	24½°
Beaver Bay	85	64	26
New Amalfi EH52	83½	64	27
New Amalfi EH20	78	63½	29½
New Amalfi	73	64½	31½
Mount Wellington (summit)	73	62	33½
St. John's Point	70½	62½	35
Mount Wellington (875 feet)	68½	61	37

Albite twins, heated to 1000° C. for 72 hours. (Average values for two twinned crystals.)

	α.	β.	γ.	$2V_\gamma$.
Esterel	88½°	64°	26½°	88°
Beaver Bay ...	86	61½	29	85
New Amalfi EH52	83½	59½	31½	78
New Amalfi EH20	79	60	32	—
New Amalfi ...	74½	61½	33	78
St. John's Point	70½	60	37	77

ated parallel to the x-axis and these show the albite-Ala fourlings described earlier. In such simple doublets or fourlings a feature of the twinning is the presence of only a few almost hair-like subsidiary albite-twin lamellae in the major albite-twinned sub-individuals. A very few extremely fine lamellae parallel to (001) presumably of pericline type are also present. The crystals elongated parallel to the z-axis are generally quite coarsely twinned polysynthetically on the albite law, the average width of the lamellae being about 0·02 mm. Carlsbad and direct albite-Carlsbad twins are also quite frequent, and it is noticeable that here too

the large Carlsbad- and albite-twinned sub-individuals are almost devoid of the fine hair-like subsidiary albite lamellae. The significance of these fine lamellae will be considered again later in this paper.

The optical orientation of this plagioclase is given in figs. 3*a*, 4, and 5 where it can be seen that both the pole of (010) for 12 twinned crystals and the position of optic axis A for 20 crystals lie in a position almost half-way between the standard low- and high-temperature curves.

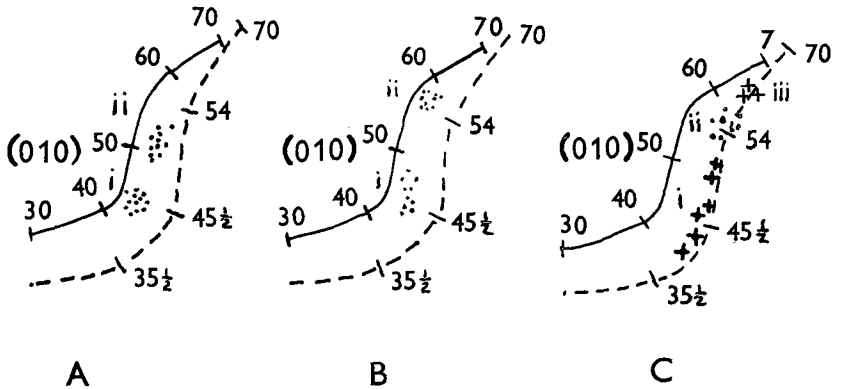

FIG. 3. Migration curves of the (010) pole for high- and low-temperature plagioclase showing the plotted positions of the poles of albite twin axes for the felspars investigated.

A (i) Andesine, from diabase M3174, Beaver Bay, Minnesota.
(ii) Labradorite from quartz-dolerite EH20, New Amalfi, South Africa.

B (i) Andesine from iron-rich quartz-dolerite EH52, New Amalfi.
(ii) Labradorite from augite-hypersthene-dolerite, New Amalfi.

C (i) Andesine, crystal fragments from Monte Rosso, Linosa, Mediterranean.
(ii) Labradorite from dolerite, summit of Mt. Wellington, Tasmania.
(iii) Labradorite from dolerite at height 875 feet, Mt. Wellington, Tasmania.

Unless the composition is known, any inference on the structural state of the felspar based on optic axes B is difficult, owing to the similar trends of the curves.

X-ray oscillation photographs were taken about all three crystallographic axes on one of the large sub-individuals of an albite-Ala fourling which plotted about the centre of the field of scatter. (The remainder of this crystal was used subsequently for refractive index determination and for heat-treatment.) The X-ray photographs showed no subsidiary reflections whatever, indicating that the mineral was structurally in the high-temperature state with a 7 Å. *c*-axis.

As the refractive indices of the Beaver Bay plagioclase would seem to

indicate a composition slightly more basic than that indicated by the (010)-face pole, it seemed possible that variation in potash content or other minor constituents might be responsible for the differences in

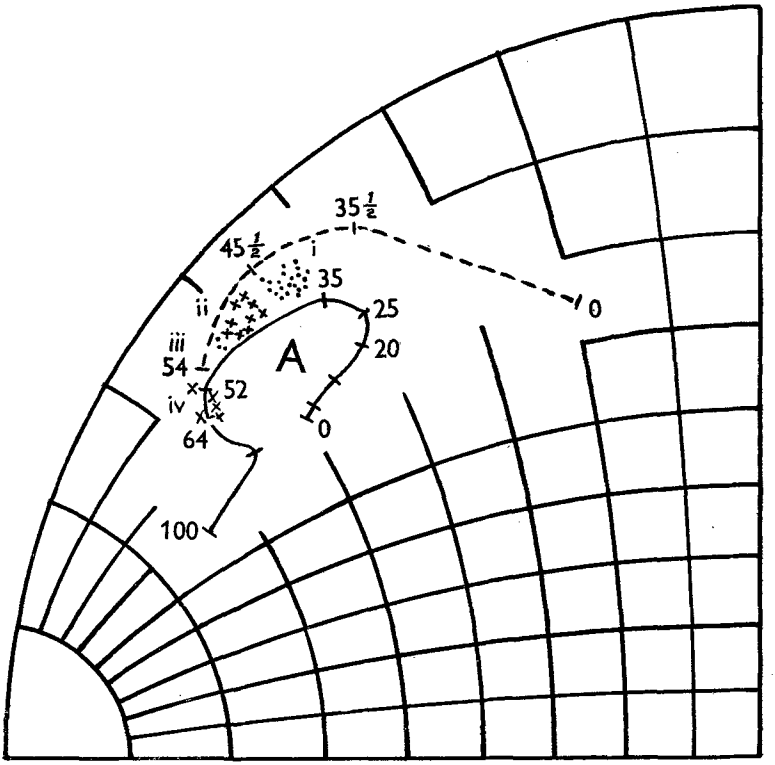

FIG. 4. Poles of optic axis A for analysed felspars.

(i) Andesine from iron-rich diabase M3174, Beaver Bay, Minnesota.
(ii) Andesine from iron-rich quartz-dolerite EH52, New Amalfi, South Africa.
(iii) Labradorite from quartz-dolerite EH20, New Amalfi.
(iv) Labradorite from augite-hypersthene-dolerite, New Amalfi.

optical orientation between this and the standard Linosa felspar $An_{45\cdot5}$. The mineral was therefore separated for chemical analysis using an isodynamic separator and centrifuge, and the final sample was examined carefully to ensure that the zoned marginal portions of the crystals and the felspar of the mesostasis had been removed. The analysis of this felspar together with that of the comparable Linosa andesine are given in columns 1 and A respectively of table II. Comparison of the two

analyses makes it clear that the potash content cannot have had any differential effect on the optical orientation, and this agrees with the conclusions of Chudoba and Engels (1937), but the higher iron content of the Beaver Bay andesine may well be responsible for the exceptionally slight differences in refractive indices of the two minerals. In the

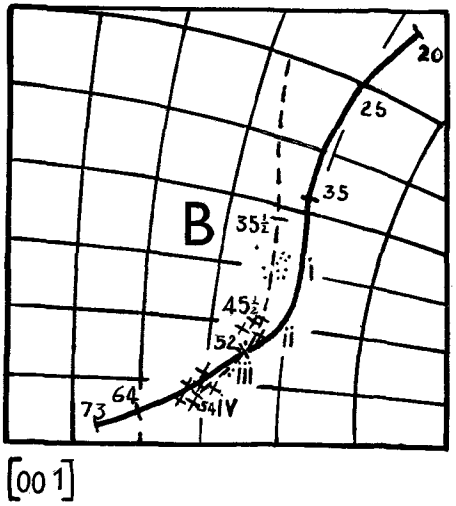

FIG. 5. Poles of optic axis B for analysed felspars.

(i) Andesine from iron-rich diabase M3174, Beaver Bay, Minnesota.
(ii) Andesine from iron-rich quartz-dolerite EH52, New Amalfi, South Africa.
(iii) Labradorite from quartz-dolerite EH20, New Amalfi, South Africa.
(iv) Labradorite from augite-hypersthene-dolerite, New Amalfi, South Africa.

Beaver Bay plagioclase there has been no exsolution of iron in the felspar such as occurs in the comparable more slowly cooled plagioclases in the ferrogabbros of the Skaergaard intrusion (Wager and Deer, 1939).

The remainder of the crystal used for the X-ray investigation and another similar albite-Ala fourling lying near the centre of the field of scatter of the (010) pole were cut out from a thin section and heated in a platinum fusion furnace for 72 hours at 1000° C. and then air cooled. They were then remounted and their optics determined again. The plotted pole of (010) now lies very close to the true high-temperature curve close to the Linosa specimen (fig. 6*b*). The positions of the optic axes are likewise affected. Optic axis A moves only slightly, but optic axis B moves down the curve towards the centre of the stereogram

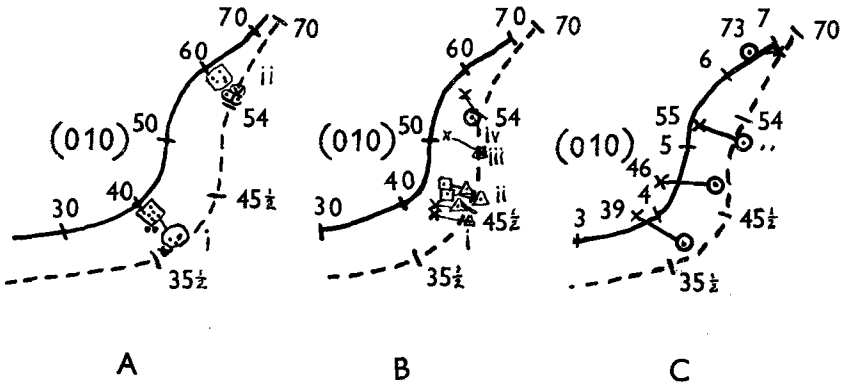

FIG. 6. Migration curves of the (010) pole for high- and low-temperature plagioclase showing the effect of heat-treatment on various felspars.

A (i) Esterel andesine for 404 hours at 1000° C. Original poles [::], after 404 hours ⊙ (C. T. Barber, 1936*b*). Plain dots, author's measurements on similar material. Position of pole after heating for 72 hours at 1000° C. is indicated by the cross.

(ii) Labradorite, St. John's Point, County Down. Original poles [::], after heating to 1000° C. for 404 hours [·] (data on heated material by C. T. Barber 1936*b*). Ringed dot, author's measurements on material heated to 1250° C. for 72 hours.

B (i) Andesine from Beaver Bay diabase. Original poles ×, after heating for 72 hours at 1000° C. as △.

(ii) Andesine from New Amalfi dolerite EH52. Original poles [·], after heating for 72 hours at 1000° C. △.

(iii) Labradorite from New Amalfi dolerite EH20. Original poles ×, after heating for 72 hours at 1000° C. △.

(iv) Labradorite from New Amalfi augite-hypersthene-dolerite. Original poles ×, after heating for 72 hours at 1000° C. ⊙.

C 39 Oligoclase An_{39} Tvedestrand. Original pole ×, after 9 hours at 1100° C. ⊙ (Scholler, 1941).

46 Labradorite An_{46} (locality not stated). Original pole ×, after 300 hours at 1100° C. ⊙ (T. F. W. Barth, Norsk Geol. Tidssk., 1931, vol. 12, pp. 57–72). [M.A. **5**–218.]

55 Labradorite An_{55} Gorodische. Original pole ×, after 8 hours at 1100° C. ⊙ (Köhler, 1941; Scholler, 1941).

73 Bytownite An_{73} Crystal Bay, Minnesota. Original pole ×, after 9 hours at 1300° C. ⊙ (Scholler, 1941).

without any marked change in 2V. There has been, therefore, a slight rotation of the position of the optic axial plane which is well shown by the displacement of its pole β in fig. 7. It would seem, therefore, that this plagioclase was not in the ultimate high-temperature state.

TABLE II. Analyses of plagioclases.

	1.	A.	2.	3.	4.
SiO_2	57·59	56·78	61·50	57·05	56·18
Al_2O_3	25·84	26·96	23·50	26·42	27·14
Fe_2O_3	0·92	0·52	0·64	0·71	0·54
FeO	n.d.	0·22	n.d.	n.d.	n.d.
MgO	trace	—	0·04	0·02	0·04
CaO	8·45	8·77	7·71	9·55	10·55
Na_2O	6·39	6·13	5·77	5·60	5·10
K_2O	0·55	0·42	0·79	0·64	0·55
H_2O+	0·32	0·26	0·39	0·16	0·16
H_2O-	0·05	0·01	0·10	0·10	0·08
	100·11	100·07	100·44	100·25	100·34
Composition Wt. %					
Or	3·1	2·2	5·00	3·7	3·1
Ab	54·1	53·1	48·73	48·0	44·5
An	42·8	44·7	38·36	48·3	53·4
			Qz ... 8·22		
Sp. gr.	2·681	2·685	—	—	—
α	1·551	1·552	1·550–3	1·553	1·556
β	1·555	1·556	1·555–8	1·558	1·561
γ	1·559	1·560	1·558–61	1·564	1·566
An	44·1	45·5	44·1	50·4	55·1

1. Andesine from iron-rich diabase, M3174. Beaver Bay, Minnesota.
A. Andesine from Linosa, Mediterranean (Ernst and Nieland, 1934, table VI); Analyst, H. Nieland.
2. Andesine from iron-rich dolerite, EH52. New Amalfi, South Africa.
3. Labradorite from quartz-dolerite, EH20. New Amalfi, South Africa.
4. Labradorite from augite-hypersthene-dolerite. New Amalfi, South Africa.

Analyses 1, 2, 3, and 4 by I. D. Muir. All refractive indices $\pm 0{\cdot}001$.

(ii) *Andesine from Monte Rosso, Linosa, Mediterranean.*

Because of the comparable compositions of the Beaver Bay andesine and one of the analysed Linosa felspars $An_{45{\cdot}5}$, it was considered desirable that specimens of this Linosa felspar should be obtained for X-ray study. As all the German material used by Ernst and Nieland and by Köhler was destroyed during the war, the study of these felspars was carried out on a number of small glass-clear crystal fragments kindly supplied by the Trustees of the British Museum. These crystals are part of the material, loose crystal lapilli, collected from Monte Rosso in Linosa by Washington and described by Washington and Wright in 1910. Washington's analyses carried out in triplicate showed the felspars to be deficient in silica, and he considered that they were solid solutions between anorthite, albite, and carnegieite and named them 'anemousite'. Later work by Ernst and Nieland, who described an

extensive collection of felspars from a similar locality in the same part of the island, established that they were chemically normal plagioclases with deviating optical properties.

The new determinations of the optical orientation, figs. 3*c* and 7, are in agreement with Ernst and Köhler's measurements and Wright's

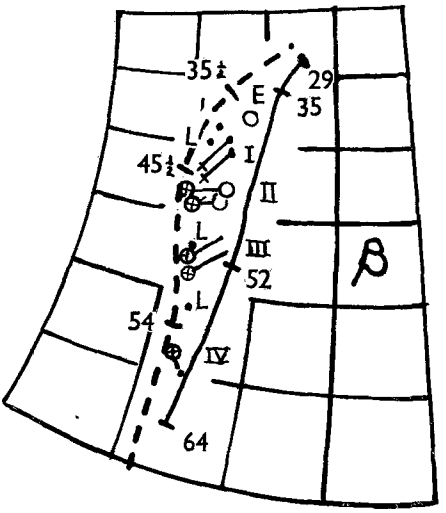

FIG. 7. Showing the rotation of the pole of the optic axial plane (β) produced by heat-treatment of various felspars for 72 hours at 1000° C.

(i) Andesine from Beaver Bay diabase M3174. Original poles •, after heat-treatment ×.
(ii) Andesine EH52, New Amalfi. Original poles ⊙, after heat-treatment ⊕.
(iii) Labradorite from EH20, New Amalfi. Original poles •, after heat-treatment ⊗.
(iv) Labradorite from augite-hypersthene-dolerite, New Amalfi. Original poles •, after heat-treatment ⊕.
E. Esterel andesine. L. Poles of fragments of Linosa felspars.

extinction angles, and confirm both Ernst and Nieland's and Washington and Wright's observations that although each crystal is quite homogeneous chemically, different crystals vary considerably in composition. X-ray oscillation photographs about the *a*-, *b*-, and *c*-axes confirm that the minerals are in the high-temperature state, having a 7 Å. *c*-axis.

In view of Washington's analytical data on this plagioclase and the doubt about the localities of the two collections, one-tenth of a gram of plagioclase free from inclusions was separated on the isodynamic

separator. Because of the limited quantity of material available (fragments from crystals of different chemical compositions) it was not possible to undertake a further separation by means of heavy liquids to obtain a chemically homogeneous sample for analysis as both Washington and Nieland had done.

TABLE III. Analysis of plagioclase from Linosa, Mediterranean.

	I.	Mol. Prop.	Or.	Ab.	An.	Σ.	
SiO_2	54·44	0·907	0·021	0·540	0·374	0·935	Composition wt. %
Al_2O_3	28·97	0·284	0·0035	0·090	0·187	0·2805	Or 1·94
Fe_2O_3	0·51	0·003	—	—	—	—	Ab 43·49
MgO	0·13	0·003	—	—	—	—	An 51·99
CaO	10·47	0·187	—	—	0·187	—	Ne 1·99
Na_2O	5·57	0·090	—	0·090	—	—	99·41
K_2O	0·35	0·0035	0·0035	—	—	—	
	100·44						Felspar to 100 %
							Or 1·8
							Ab 46·7
							An 51·5
	A.						
SiO_2	52·77	0·8795	0·048	0·522	0·380	0·950	Composition wt. %
Al_2O_3	29·50	0·289	0·008	0·087	0·190	0·285	Or 4·32
Fe_2O_3	0·65	0·009	—	—	—	—	Ab 37·52
FeO	0·17	—	—	—	—	—	An 52·32
MgO	0·05	—	—	—	—	—	Ne 5·24
CaO	10·66	0·190	—	—	0·190	—	99·40
Na_2O	5·40	0·087	—	0·087	—	—	
K_2O	0·74	0·008	0·008	—	—	—	Felspar to 100 %
H_2O-	0·36	—	—	—	—	—	Or 4·3
	100·30						Ab 44·3
							An 51·4

I. Plagioclase from Monte Rosso, Linosa. Collected by H. S. Washington. Analyst, J. H. Scoon.

A. Plagioclase ('anemousite') from same locality. Average of three duplicated analyses by H. S. Washington. (Washington and Wright, 1910.)

The analysis was carried out on a semi-micro scale by Mr. J. H. Scoon, and the results are quoted in table III along with Washington's average of three analyses. From the recalculation of the analysis it is clear that it conforms well with the plagioclase structural formula, as do the analyses by Nieland.

Another analysed high-temperature plagioclase conforming with the curves determined for the Linosa minerals is that from the andesite (An_{38}) of Mayeamo, Japan, described by Becke (1921).

(iii) *Andesine* An_{40}, *NW. of Agay, Esterel, France.*

This famous andesine occurs as phenocrysts in an andesite and is associated with a deep-bluish amphibole. It is mentioned by Köhler (1941) but was not used for drawing up his curves because it deviated from them. Actually Köhler quotes the position of optic axis A incorrectly in his paper and the author's data agree with Becke's and Barber's measurements (fig. 6). On heat-treatment the pole of (010) which lies off the low-temperature curves moves on to the high temperature curve at about the appropriate composition and the optic axes also show a slight movement. These results too are in agreement with those obtained by Barber (1936*b*) on the same material. X-ray oscillation photographs on the unheated mineral confirm that it too has a 7 Å. *c*-axis. It must be concluded, however, that this mineral also is not truly in the ultimate high-temperature state.

(iv) *Andesine* An_{45-48}, *New Amalfi intrusive sheet, South Africa.*

Three plagioclases from this intrusion have been studied, one from the iron-rich facies of the dolerite being the most sodic. The rock from which the plagioclase was separated (EH52, Poldervaart, 1944) is rather similar in petrographic character to the Beaver Bay specimen. The ferroaugite is of similar composition to the Beaver Bay one but the exsolution lamellae parallel to (001) are more conspicuous. No separate pigeonite occurs and there is a little interstitial primary orthopyroxene (Of_{73}) and olivine (Fa_{85}).

The plagioclase has the same general textural features as the Beaver Bay andesine but is more markedly zoned towards the margins. Albite-Ala fourlings are again present and were used for determining the optical orientation. Unlike the Beaver Bay and Esterel andesines, this mineral exhibits very fine hair-like albite lamellae within the principal twin sub-individuals. Because of the more pronounced zoning of this felspar, the central portions of the crystals only were used for determining the optical orientation.

The results of the optical measurements made on this plagioclase are given in the composite stereograms, figs. 3*b*, 4, and 5, where it can be seen that both the (010) pole and of optic axis A (for ten crystals) lie in positions nearly half-way between the high- and low-temperature curves at compositions averaging about 46 % An. This composition is confirmed by the refractive index measurements made on a specimen near the centre of the field of scatter. A portion of this crystal was used for heat-treatment.

Oscillation photographs of the unheated material show only a few very feeble subsidiary doubled type '*b*' reflections on the *c*-axis photographs. On heat-treatment for 72 hours at 1000° C. the poles of (010) and β move close to the high-temperature curves.

The optical and X-ray data both confirm that this plagioclase also is in a transitional state, but is in a rather different structural condition to the Beaver Bay andesine because of a rather slower rate of cooling—a conclusion which had already been inferred from the broader nature of the exsolution lamellae of the ferroaugite in the New Amalfi rock.

An analysis of the plagioclase fraction separated from this rock is given in table II, column 2. In this case it is clear that the analysed material contained about 10 % of quartz from the groundmass of the rock and also a proportion of the more sodic late plagioclase.

(v) *Labradorites from the New Amalfi intrusive sheet, South Africa.*

In order to obtain a clearer idea of any relation between the structural state of the plagioclase and exsolution and inversion of the associated pyroxenes, two felspars from earlier two-pyroxene rocks of this intrusion were examined and analysed.

The first of these (EH20, Poldervaart, 1944), from a rock which must have crystallized from a liquid very close to the limit of the two-pyroxene field, contains ferroaugite $Ca_{35}Mg_{31}Fe_{34}$ (α 1·706, β 1·711, γ 1·733, 2V 48–50°), with exsolution lamellae parallel to (001) which are perhaps a little coarser than those of the ferroaugite of EH52. The lime-poor pyroxene was a pigeonite and is now represented by orthopyroxene (β 1·731, 2V 53°) Of_{59} with fine but distinct exsolution lamellae of augite parallel to the original (001). The plagioclase (An_{51}) is generally similar to that of EH52, but is much less strongly zoned and contains relatively few large untwinned areas. Around the margins of such areas as remain untwinned the hair-like subsidiary albite-twin lamellae pinch out. Twinning is chiefly on the albite, Carlsbad, and pericline laws. Optical measurements show that for this felspar the plotted poles of (010) lie again in an intermediate position between the high- and low-temperature curves (fig. 3*a*).

The second plagioclase studied (An_{55}) came from a more basic rock of the same intrusion. The associated pyroxenes are augite $Ca_{37}Mg_{53}Fe_{10}$ (α 1·674, β 1·680, γ 1·702, 2V 40–48°, average value 44°), and orthopyroxene Of_{39} (β 1·712, 2V 53°) with fine well-developed exsolution lamellae of augite parallel to (100) and an outer zone containing abundant inclusions of the same mineral. The augite contains two sets of ex-

solution lamellae, a broad set parallel to (001) and a much finer set parallel to (100). On the evidence of the pyroxenes this rock would seem to have cooled much more slowly than the preceding one.

The plagioclase (An_{55}) is clear, unaltered, and devoid of zoning. It builds short subhedral crystals with broad (0·1 mm.) distinct twin lamellae, contains relatively few large untwinned areas, and has the usual fine hair-like albite twin lamellae. Twinning is chiefly on the albite, albite-Carlsbad, pericline, and Carlsbad laws, and one example of Manebach-acline twinning was observed. The plotted pole of (010) deviates only slightly from Reinhard's (low-temperature) curve but lies on the curves of Spaenhauer as given by Barber (1936*a*) and of van der Kaaden (1951). On heating to 1000° C. for 72 hours the poles of (010) of selected crystals of both of these specimens moved on to the high-temperature curve at the appropriate compositions (fig. 6*b*).

X-ray oscillation photographs of both specimens show that the type '*b*' reflections are doubled in the normal manner of the intermediate plagioclases; but a rough comparison of the relative intensities of the subsidiary reflections for a particular oscillation range suggests that those of the second specimen are slightly stronger than those of the first, and the character of the pattern for the second specimen is that of a normal low-temperature plagioclase. It is known (Gay, 1954) that the intensities of the subsidiary reflections fade on heating but the precise variation in the intensities of the subsidiary reflections with composition is not known. For the range An_{51-55} the intensity change (if any) will be very small, so it seems reasonable to suggest that the first specimen (EH20) with the slightly weaker reflections is not completely inverted but is not far from the true low-temperature state. A full account of the X-ray patterns of these and other felspars mentioned in this paper will be included in a later publication by Gay describing X-ray work on the intermediate plagioclases.

V. The relation between exsolution and inversion of the pyroxenes and the structural state of the plagioclase.

The study of the specimens described in the previous section shows clearly that there is a definite relation between exsolution and inversion in the pyroxenes whose compositions are plotted in fig. 8, and the structural condition of the associated plagioclase. Where iron-rich pigeonite remains, as in the rocks from the summit of Mount Wellington, Tasmania, the plagioclase (An_{55}) has remained in the high-temperature

state, as the plotted positions of the (010) poles demonstrate quite clearly (fig. 3*c*). In this rock very fine exsolution lamellae of pigeonite can also be observed in the ferroaugite. At Beaver Bay some of the pigeonite has inverted to orthopyroxene and the plagioclase (An_{44}) is in a transitional condition although it still retains its 7 Å. *c*-axis. The

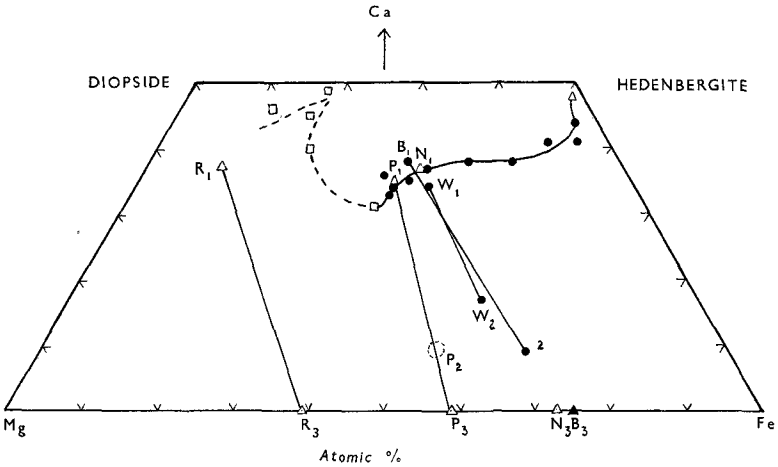

FIG. 8. Pyroxenes associated with felspars from tholeiitic rocks discussed in this paper. Comparison is made with the normal clinopyroxene trend of the Skaergaard intrusion (Muir, 1951). In this diagram the lime-content of the orthopyroxenes is ignored.

• Analysed pyroxenes. △ ▲ Composition estimated from optical properties. □ Clinopyroxene composition recalculated from analysis of bulk pyroxene of the rock.

B. Beaver Bay diabase M3174. B_1 ferroaugite, B_2 pigeonite, B_3 primary orthopyroxene.

N. New Amalfi iron-rich dolerite EH52. N_1 ferroaugite, N_3 primary orthopyroxene.

P. New Amalfi quartz-dolerite EH20. P_1 ferroaugite, P_3 inverted orthopyroxene, P_2 inferred composition of original pigeonite.

R. New Amalfi augite-hypersthene-dolerite. R_1 augite, R_3 primary orthopyroxene.

W. Mount Wellington sill, Tasmania. Dolerite of summit. W_1 ferroaugite, W_2 pigeonite. (Analyses to be published in a later paper.)

next stage is represented by the minerals of the rock EH52. Here exsolution lamellae in the ferroaugite are better developed and the plagioclase (An_{46}) now shows feeble subsidiary reflections. A still slower rate of cooling is represented by the rock EH20 where the pigeonite has just inverted and the plagioclase (An_{51}) is still not completely in the

low-temperature state. In this rock the exsolution lamellae of the ferroaugite still retain their oblique extinction and high birefringence, and appear to be pigeonite. No rock containing the necessary iron-rich pyroxenes could be found to serve as an example of the final stage, which is represented instead by the minerals of the last specimen described where the pyroxenes are rich in magnesia. In this rock the augite contains very broad exsolution lamellae parallel to (001) composed of orthopyroxene—the exsolved material itself having inverted from pigeonite. The plagioclase of this rock is in the normal low-temperature state.

VI. The development of secondary twinning in plagioclase.

A significant feature of several of the crystals subjected to heat-treatment was the development of new albite and pericline twinning. Possibly the best illustration of this was afforded by the heat-treatment of a primary albite-twin crystal of the Beaver Bay andesine (fig. 9*a*). Before heating, this crystal contained only a few very fine hair-like subsidiary albite twin lamellae (arrowed in figure) and no lamellae of pericline type. After heating, the subsidiary albite lamellae had become much more numerous and a few of pericline type had also appeared. A similar development of new twinning by heating has been reported by Scholler (1941) in the bytownite (An_{73}) from Crystal Bay, Minnesota. It has been observed also by the author in heat-treated specimens of labradorite (An_{62}) from St. John's Point, Co. Down, on which X-ray data have been provided by Gay and Taylor (1953), and an anorthite An_{98} from Pasmeda Alp, Fassa. The production of fine albite and pericline twinning is also recorded by Tuttle and Bowen (1950) in heat-treated Amelia albite. The twinning in this case can probably be attributed solely to the low–high temperature inversion, for the differences between low- and high-temperature albite are of considerably greater magnitude than those existing between comparable low- and high-temperature forms in the more basic plagioclases.

No obvious explanation of this new twinning can be offered, at this stage, on the above evidence alone, but it is of interest to note that all three intermediate plagioclases in which it was developed are transitional types close to the high-temperature structural state and contain large untwinned areas.

In order to investigate further the significance of this fine twinning, two plagioclase crystals from the specimen EH20 where the mineral is close to the low-temperature state were selected for heat-treatment

and cut out of a thin section. These crystals showed what was regarded as a partial development of secondary twinning (fig. 9*b*), and contained relatively large untwinned areas. These are uncommon in this plagioclase. Unfortunately, the crystals broke up on being removed from the crucible after heat-treatment at 1000° C. for 72 hours, but examination

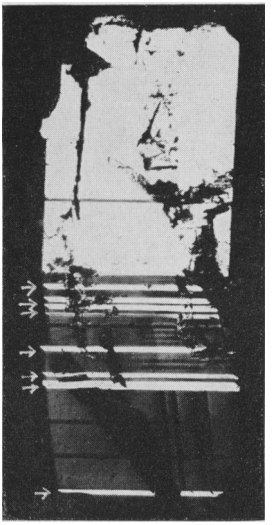

FIG. 9*a*. Albite-twinned plagioclase crystal from Beaver Bay diabase, showing newly developed albite and pericline twin lamellae after heat-treatment for 48 hours at 1000° C. Original lamellae indicated by arrows. ×50.

of the heated material revealed numerous fine albite-twin lamellae and no large untwinned fragments. Similar fine lamellae may be observed in many low-temperature plagioclases which are thought to have passed through the high-temperature state.

The twinning of another crystal (fig. 9*c*) from this specimen is of interest. This crystal is one of the rare examples in the rock where a large primary albite-twin sub-individual is almost devoid of subsidiary lamellae. The other sub-individual, however, has well-developed lamellae of albite and pericline type. Both halves of the crystal are zoned to a similar degree at the margins to An_{42}, but the central portions of the crystal are quite homogeneous and have the same composition (An_{51}). Although repeated measurements on the universal stage gave consistent results in all four major sub-individuals it was impossible to locate the albite twin axis accurately on the projection because of the large triangle of error formed by the intersections of the great circles. The reason for

this became obvious when the poles of (010) for the two major sub-individuals were plotted on a stereogram using the cleavage and composition plane as reference directions (fig. 10). From this it can be seen that there is no difference in composition between the two sub-

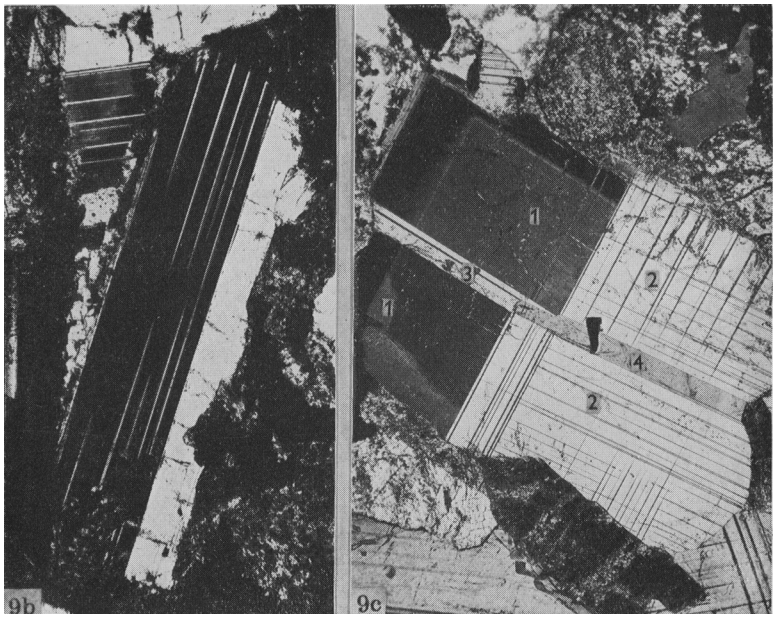

FIG. 9*b*. Andesine crystal from quartz-dolerite EH20, New Amalfi, South Africa, showing a partial development of subsidiary albite-twin lamellae around the margins of the crystal. ×24.

FIG. 9*c*. Primary albite-twinned plagioclase from quartz-dolerite EH20, New Amalfi.

Sub-individuals 1 and 2 albite twinned; 1 and 3, and 2 and 4 pericline twinned. Note the development of fine subsidiary twin lamellae in the right-hand side of the crystal only. ×24.

individuals, but it seems likely that the inversion has proceeded farther in that portion of the crystal in which the subsidiary twin lamellae are abundant. The difference in the mean positions of the plotted poles ($3\frac{1}{2}°$) is significant, but must be regarded as being just within the limits of experimental error in view of the fact that the (010) composition plane and cleavage, and not the twin axis, must be used as a reference direction in cases such as this. It is hoped that it will be possible to carry out

further work on similar crystals supported by X-ray work to try and confirm the conclusions suggested here by the optical data.

The evidence thus far would seem to indicate that the development of this secondary twinning was in some way dependent on the rate of cooling. It might be thought that this twinning would be induced by the strain caused by the inversion from the high- towards the low-temperature state; but if this was the case then it is difficult to understand, firstly, why new lamellae are produced by heating the mineral

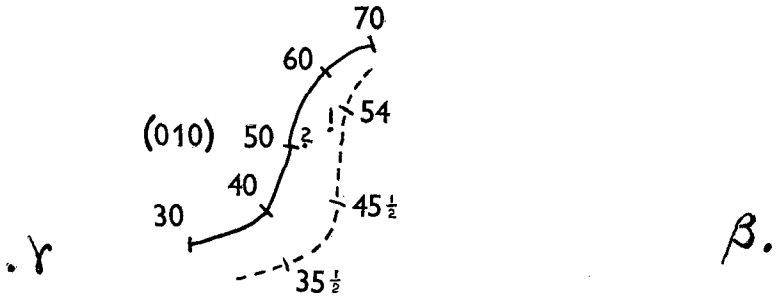

FIG. 10. Migration curves for high- and low-temperature plagioclases, showing the positions of the (010) face pole for the two major sub-individuals of the crystal illustrated in fig. 9*c*.

when they should disappear, and secondly, why intermediate plagioclases can exist apparently quite stably in various transitional states if considerable structural strain is induced by the inversion. Rather does it seem that the secondary twinning was incipient in the original high-temperature plagioclase and developed during slow cooling as a separate feature which may be independent of the inversion. In this case subsequent annealing to 1000° C. could allow more of these fine lamellae to develop.

Careful detailed studies of plagioclase twinning have shown that much of the twinning seems to be primary. The fine lamellae present in many intermediate plagioclases seem to be of secondary origin. It may well be that many of the coarser polysynthetic lamellae of natural igneous plagioclases have a similar origin, for many of them seem to have developed late in the history of the crystal. Only a long and detailed study of high-temperature, transitional, and low-temperature plagioclases of similar compositions and parageneses will be able to shed further light on this problem, the solution of which might have great petrogenetic significance.

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