An investigation of high-temperature optics in some naturally occurring plagioclases.

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Introduction.

FOR several years now it has been generally appreciated that plagioclase felspar formed at high temperature differs optically from that formed at lower temperatures. Much of the evidence for this has been provided by the Austrian workers, notably Köhler (1-3), Scholler (4), and Tertsch (5–7), who have prepared revised curves to supplement the universal-stage stereograms of Reichert (which are for use with low-temperature material). There are a number of interesting petrological points which have not yet been fully investigated. Much work has been done on synthetic material, and it is not clear to what extent the high-temperature forms occur naturally. There may be two distinct and separate types of plagioclase structure, or the two forms may grade into one another. It may be possible to explain the optical anomalies as an order-disorder phenomenon; a more disordered state has been 'frozen-in' in those felspars which have formed at a high temperature and cooled rapidly. A more detailed understanding of the conditions required for the production of high-temperature optics would be a useful aid in questions of petrogenesis.

The present work was undertaken in the hope of obtaining further information on some of these points. The plagioclase-bearing rocks selected were of a variety of types and included some in which it appeared reasonable to expect high-temperature felspars. The plagioclase in each rock was studied in detail using universal-stage and refractive-index methods and the results obtained were compared.

It is not proposed to give here an exhaustive survey of earlier work in this field, merely to comment on some of the more important aspects. Useful surveys of the methods and conclusions of the Austrian workers have been given by Köhler (3) and, more recently, by Reynolds (8), who also provides a valuable bibliography. The use of drastic heat-treatment to produce high-temperature optics in plagioclase has been tried by

Barth (9) and Barber (10) with varying success. Oftedahl (11, 12) and Barth (13) have done much work on plagioclases found in the rocks of the Oslo igneous complex in testing the results of the Austrian workers. Their results agree partially, but not completely, with the high-temperature curves of Köhler, and they postulate an intermediate transition series between the high- and low-temperature plagioclases—the position of any one crystal depending on the rate of cooling as well as the temperature of formation. In addition, they checked the universal-stage results against refractive-index determinations and found that for high-temperature felspar the universal-stage values were consistently higher in anorthite than the refractive-index values. Rhomb-porphyry plagioclase phenocrysts had universal-stage results 7–9 % higher in anorthite content, while a phenocryst from a basalt gave 61 % An compared with the 48 % found by refractive-index determinations. Köhler (1949) also reported that the standard Reichert curves, when used with high-temperature plagioclase, gave an An content 10–15 % too high.

The plagioclase phenocrysts of some Hekla lavas have been investigated by H. Sørensen (14), who found that some felspars in the devitrified lavas had cores with high-temperature optics and an outer, more calcic zone, with low-temperature optics. Some divergence from Köhler's curves is attributed to a difference in composition between adjoining twin individuals. Turner (15, p. 397) also reports 'A discrepancy between the values for composition as determined [by universal-stage measurements] in different pairs of subindividuals belonging to a single crystal . . . is by no means uncommon'. This anomaly has been observed by other workers and appeared again in the course of this investigation; it is most readily interpreted as a difference in composition between the two subindividuals. Köhler's method of plotting cannot be expected to give accurate results in such cases.

Source of material.

The object of the study was the natural occurrence of high-temperature plagioclase. Six specimens from the collection at King's College were selected for investigation. Porphyritic pitchstones were thought to be a likely source for such felspars and three were selected, two from Arran and one from Tenerife. Other rocks, expected to carry low-temperature material, were investigated at the same time. These were an olivine-gabbro (Stonehead, Aberdeen), a hornblende-pegmatite (Ronez, north Jersey), and a leuconorite (Bushveld complex, South Africa). The rock types are described briefly below and the plagioclase they contain is commented on in rather more detail.

Universal-stage measurements.

The universal stage used was the Leitz 4-axis model, and the technique for the determination of the plagioclases was broadly that given by Reinhard (17). Each crystal was measured at more than one point—where possible on two or more adjoining twin individuals. Albite (or more rarely, pericline) twin lamellae were present in all the felspars, and the position of the composition plane of the twin lamellae was measured directly for each crystal. It was not possible to use the cleavage traces as a second reference plane, since the cleavage was very variable—excellent in the leuconorite, for example, but not visible in the hornblende-pegmatite. The cleavage was also poor in the pitchstone plagioclases: it is possible that good or bad cleavage, which appears consistent for all the slides made from one rock specimen, is in some way related to the homogeneity of the crystal—or possibly to the thermal history.

In the cases where two adjoining twin individuals were measured it was also possible to determine the anorthite content from the twinning relationship between them; this provided a useful check on the value obtained from the direct measurement of the composition plane. Any results where the stereographic plot showed a divergence of 2 or more degrees from the 90° relationship between the optic planes were discarded. It was interesting to note that many of these inaccurate measurements had one feature in common: the optic axial plane, which was measured directly, was so placed that the two optic axes were lying at 25° or more from the vertical. It appears that it is difficult to measure an optic axial plane in this position accurately, presumably because the optic axes obscure the true extinction position.

The results of measurements made on a number of crystals are shown in each of the composite stereograms (figs. 1–6). The stereogram curves are taken from those prepared by Reinhard (17). Selected parts of his tables 2 and 5 have been combined: n_β is always in the centre of the stereogram, and in each case the continuous curves refer to the poles of normal 'parallel' twins and to the cleavage directions; the broken lines refer to the poles of 'edge' twins.

Olivine-gabbro, Stonehead, Aberdeen.—This is a familiar rock-type which is used as part of a teaching collection. The minerals present include a ragged red-brown mica, augite, abundant olivine, colourless apatite, and iron-ore. The olivine shows partial but limited alteration;

some of the augite crystals have regularly arranged rod-like inclusions in two directions. The plagioclase is in fresh condition and has good cleavage. The crystals may be composite and intergrown, with irregular edges and varied twinning. Pericline is much less common than albite twinning. The multiple-twin lamellae are often very broad; in some cases the lamellae extend only part of the way along the crystal and may taper to a finish—making an accurate determination of the composition plane very difficult. No regular zoning was observed, but the extinction in some crystals is rather patchy.

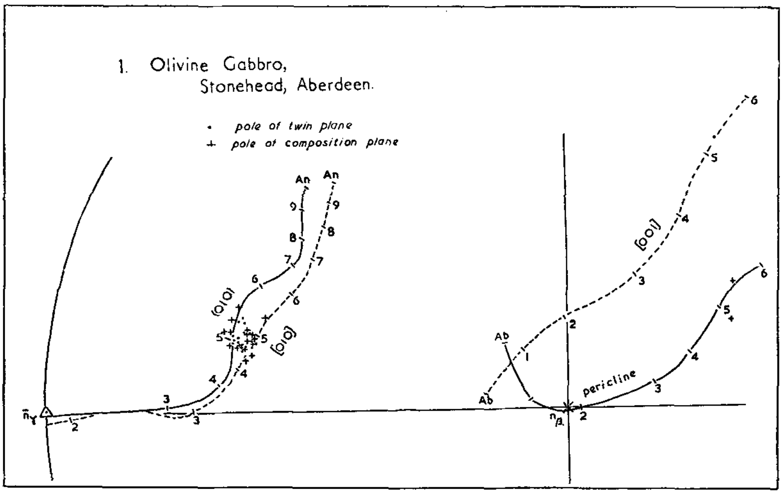

FIG. 1. Composite stereogram of plagioclase from olivine-gabbro, Stonehead, Aberdeen.

The composite stereogram (fig. 1) shows mainly albite twinning. The poles of the twin planes are less scattered than those of the composition planes; this is to be expected, since the position of the composition plane is determined by a single, possibly inaccurate, measurement, while the twin plane is found as a relationship between two separately-measured crystal individuals so that individual errors of measurement will have less effect. The plagioclase shows little variation in composition, 5–6 % only, and this homogeneity is confirmed by the other measurements on pericline and (001) twinning. The small displacement to one side of the (010) curve appears to be systematic rather than random, but the cause of this is not known. In other respects this is a normal low-temperature mineral, with little variation either in optics or composition.

Hornblende-pegmatite, Ronez, north Jersey. An unusual type of rock of uncertain antecedents, but probably formed at a low (pegmatitic) temperature. It is coarsely crystalline and formed principally of hornblende and plagioclase with subordinate amounts of quartz, apatite, zircon, and iron-ore. The quartz is interstitial. Partial alteration of hornblende to pennine is common and the pennine is often spherulitic. Crystal boundaries are irregular and intergrown. There are clearly two

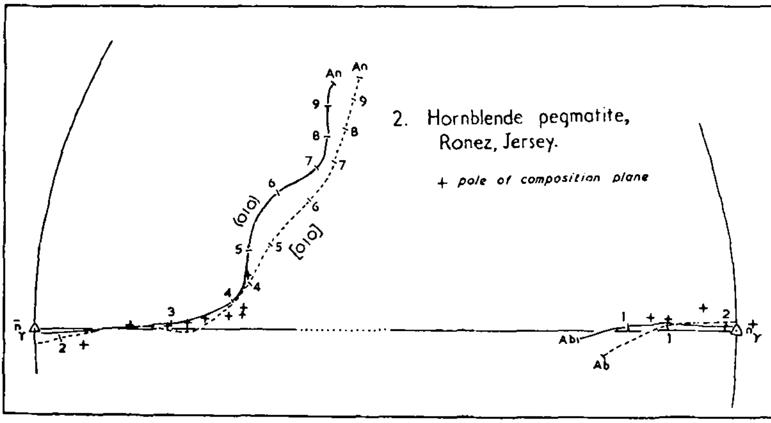

FIG. 2. Composite stereogram of plagioclase from hornblende-pegmatite, Ronez, Jersey.

hornblendes: an earlier-formed red-brown hornblende forms the cores of the crystals, and a later, marginal, pale-green mineral is in optical continuity with it. The brown hornblende has opaque relic inclusions regularly spaced at an oblique angle to the cleavage. Plagioclase occurs as large simple crystals, often partially or almost wholly decomposed; in some cases there is a selectively altered core. The most striking feature of the felspars is the strongly marked simple zoning—the so-called normal zoning with a core more basic than the margin of the crystal. Cleavage was not visible in the sections prepared.

Albite twinning is common, but only one set of the twin lamellae is broad enough for the optics to be measured accurately. The lamellae may extend only part of the way along the crystal. Twinning on other laws, such as Carlsbad, does occur, but is uncommon, and the universal-stage measurements had to be confined to the composition planes of the albite twins (fig. 2). A single measurement like this can lead to ambiguous results in plagioclase with low anorthite content. This ambiguity has been overcome as far as possible, firstly by comparative refractive-index measurements and secondly by measuring at several points across the crystal. Since the zoning is continuous, not oscillatory, the combined series of results can generally be interpreted in only one way. As shown in the stereogram, the range in composition is large, more than 30 % An; the variation measured in a single crystal is 16 % An. Zoned crystals

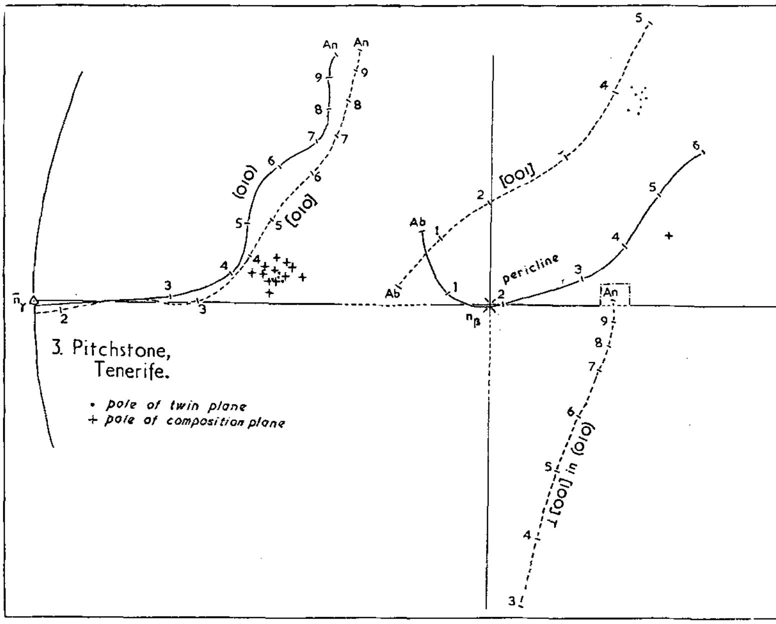

FIG. 3. *Composite stereogram of plagioclase from porphyritic pitchstone,* Tenerife.

are difficult to measure accurately and the (010) composition-plane poles approximate as closely to the low-temperature curve as could be expected. The evidence in favour of these plagioclases being formed at a low temperature is consistent with the coarse-textured pegmatitic facies in which they occur.

Porphyritic pitchstone, Tenerife.—The pitchstone has a microcrystalline groundmass with many isotropic patches and some iron-rich segregations. Phenocrysts other than plagioclase include an idiomorphic hornblende and a clinopyroxene often intergrown with iron-ore. The plagioclase is in two generations: in addition to the large phenocrysts there are numerous tiny lath-like crystals scattered throughout the mass and fluxionally arranged. The large phenocrysts are also lath-shaped, and elongated parallel to [010]. They are sometimes composite, and although fresh have many small inclusions. Cleavage was not seen in the prepared sections. The larger twin individuals have a somewhat patchy extinction suggesting that the composition is not quite uniform; regular concentric zoning was not observed. The phenocrysts show both single and repeated twinning, mainly parallel to the direction of elongation. The albite twin lamellae are often very narrow, may extend only part of the way down the length of the crystal and terminate irregularly. The twinning is sometimes complex, in several directions within a single crystal. The composite stereogram (fig. 3) for this plagioclase is considered together with that for the Glen Cloy felsite felspar.

Porphyritic felsite, Glen Cloy, Arran.—The matrix, which was once spherulitic, is now devitrified and difficult to interpret. The texture is variable and the groundmass may include considerable amounts of chlorite and calcite. There is some iron-ore present, but the only phenocrysts are of plagioclase and these often occur in groups. The plagioclase is badly decomposed, and there is much secondary development of calcite. The crystals were originally euhedral, mainly equidimensional, although some are lath-shaped; they show evidence of corrosion prior to decomposition. The size-range of phenocrysts is considerable. The albite twin lamellae are thin and not very numerous. There is some zoning, mainly from the centre to the margin of the crystals. It is difficult to interpret either the twinning or the zoning because of the decomposed nature of the crystals. Plagioclase also occurs as a mosaic of small crystals, with some groups in optical continuity.

The stereograms for Tenerife (fig. 3) and Glen Cloy (fig. 4) felspars have much in common and may be considered together. In both cases there is a systematic displacement from each of the three curves, (010), [001], and $\perp$[001] in (010). The composition of both plagioclases is about 40 % An and shows little variation. The displacement of the (010) twin-plane poles from the low-temperature curve is considerable, and is at least as great as that of the composition-plane pole (as with the other stereograms, the poles of the composition plane show greater scatter). Thus these two groups of plagioclase crystals, although markedly different in habit, show similar anomalous optics, due probably to a similar petrogenesis; whether these anomalies are the full high-temperature optics is discussed later.

Porphyritic pitchstone, Brodick, Arran.—This is one of the more attractive of the Arran pitchstones with many acicular and arborescent crystallites set in an isotropic matrix. The pale-green acicular crystallites are probably pyroxene. Phenocrysts are of quartz, plagioclase,

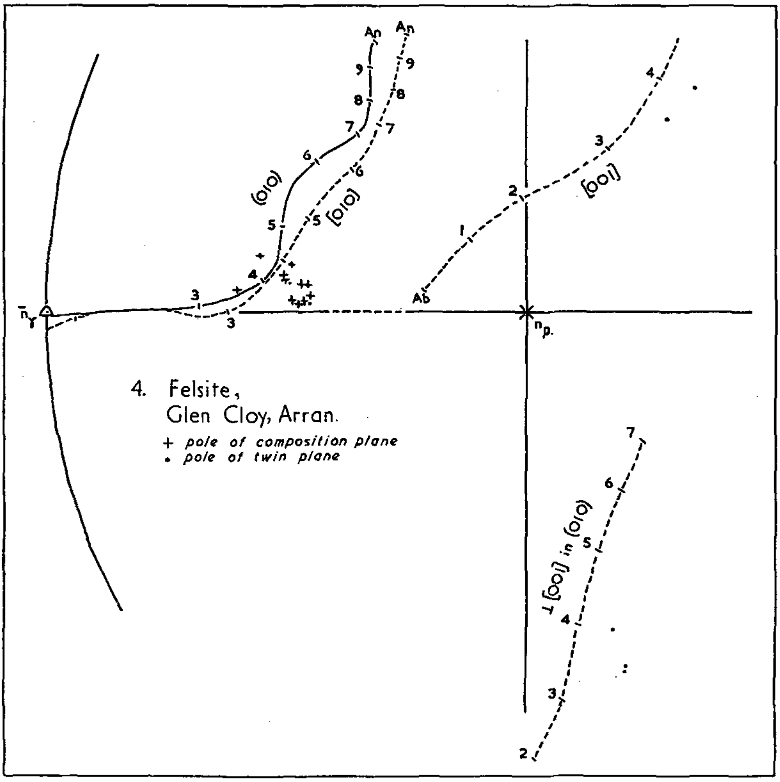

FIG. 4. Composite stereogram of plagioclase from porphyritic felsite, Glen Cloy, Arran.

and pyroxene; the pitchstone is known to carry olivine also, but this is not present in the sections prepared. The quartz phenocrysts were originally euhedral, but are now much corroded. Undulose or strain extinction is not conspicuous. A striking feature is the spherulitic fringe of large and small crystallites bordering each quartz crystal. Porphyritic pyroxene is much less abundant; the crystals are euhedral to subhedral, pale-green in colour and non-pleochroic. The plagioclase phenocrysts are equidimensional and variable in size; they are sometimes grouped together in a unit of several unrelated crystals, or intergrown with pyroxene and iron-ore. The felspar crystals are euhedral, but may show some evidence of corrosion. Acicular crystallites form a fringe around the felspars which differs from the spherulitic fringe of the quartz phenocrysts, since here the crystallites are orientated at right

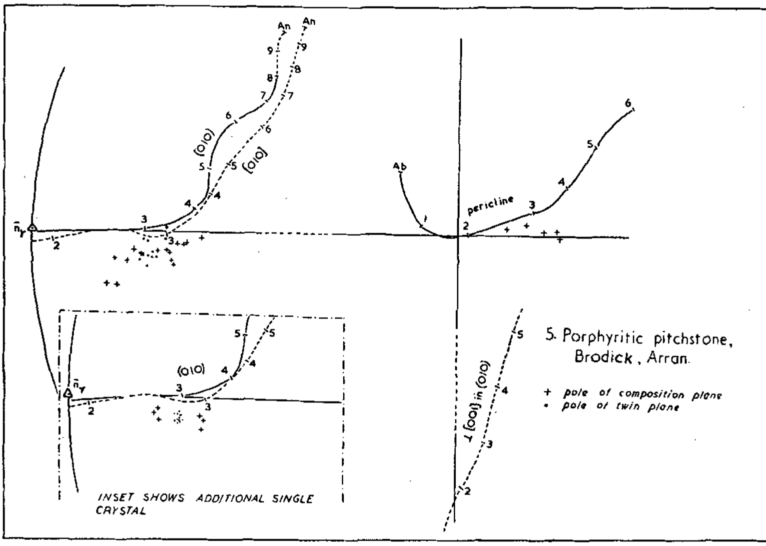

FIG. 5. Composite stereogram of plagioclase from porphyritic pitchstone, Brodick, Arran.

angles to the crystal edge. The twinning is often complex and the twin boundaries may be irregular. Individual twin bands tend to be rather broad and some crystals show a considerable patchiness under crossed nicols, a phenomenon that is perhaps too irregular to be satisfactorily termed zoning.

The plagioclase in this rock is more acid (An_{30}) than that of the other two pitchstones. The displacement from the normal curves (fig. 5) is in the same direction as it is in figs. 3 and 4. The most interesting feature is the way in which the composition shown by the twin-plane measurements on (010) is often intermediate between the values obtained from measurements on the composition plane of alternate albite twin lamellae. (This is well illustrated by the inset stereogram of a single crystal.) If there is a difference in composition between adjoining twin lamellae, the determination of the twin plane between these adjacent individuals gives an anorthite value intermediate between that obtained for the two lamellae.

It is significant at this point to recall the recent X-ray work on the structure of the plagioclases (Cole, Sörum, and Taylor (18)). Here it was shown that the albite structure persists up to about An_{30} and the anorthite structure is stable above An_{72}. The intermediate plagioclases between these two limits of composition have a third type of structure consisting of alternating slabs of An-type lattice and Ab-type lattice. The intermediate structures are believed to be superlattices, and it is possible to disorder the structure by appropriate heat-treatment. The transition from the intermediate to the other structures may occur at some other composition value under different conditions of crystallization—it may not even be present for the high-temperature plagioclases. With this work in mind it is not difficult to appreciate that a felspar with a composition near one of these transition points may exhibit unusual features, particularly if cooled rapidly from a high temperature of formation. It may be, for example, that above a certain temperature the two types of structure form simultaneously. Thus at the albite-intermediate transition point, an albite-type structure ($An < 30$) might form at the same time as an intermediate-type structure ($An > 30$ %). With slow cooling the structure would be able to stabilize itself by some form of reorientation. If the cooling is rapid, as with a pitchstone, the differences may be 'frozen-in', and might be expected, as in the Brodick example, to have controlled to some extent the formation of the twin lamellae. The refractive-index measurements, discussed later, demonstrate that for these Brodick crystals, the alternating twin lamellae have compositions above and below about An_{20} rather than An_{30} %. This variation in composition between adjoining twin lamellae may prove, when better understood, to be useful for analysing the thermal history of plagioclases with a suitable anorthite content.

Leuconorite, Bushveld complex.—A rock formed of two minerals only, plagioclase and orthopyroxene, the former in considerable excess. The texture of the rock and the relationship between the two constituents have been discussed in a recent paper by Wells (16). The explanation proposed is essentially one of simultaneous crystallization with sometimes one mineral slightly in advance and sometimes the other. Both minerals have rounded and intergrown boundaries. The plagioclase is very fresh and has excellent cleavage. The crystals are intergrown but not composite or complex. Twin planes are characteristically sharp and straight—only very occasionally are the boundaries irregular or tapering. The albite twin lamellae are broad, and adjoining twins can usually be measured. The plagioclase from this rock, with An_{70-80}, is more basic than the other material investigated. There was no particular

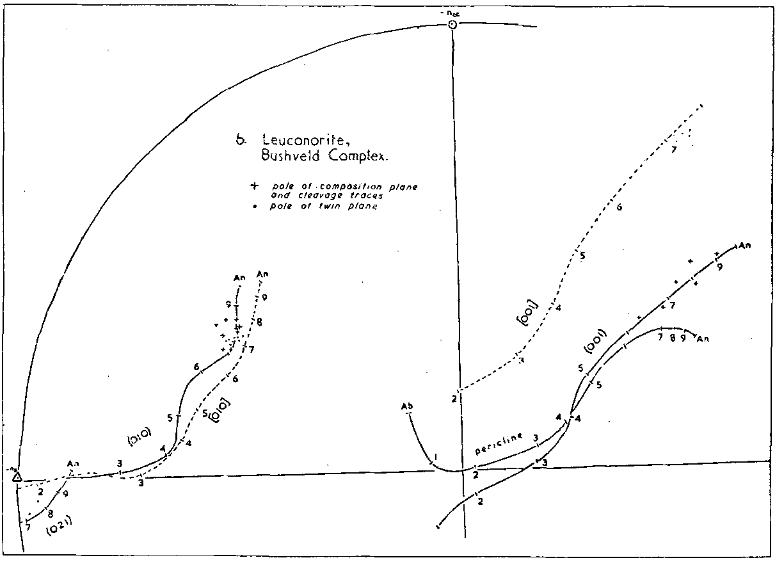

FIG. 6. Composite stereogram of plagioclase from leuconorite, Bushveld complex, South Africa.

reason to expect it to show high-temperature optics, but, on the other hand, the composition range includes the point where the second change in structure takes place: the X-ray work has shown the anorthite-type structure to be stable with more than An_{72}; with less anorthite the intermediate-type structure is formed.

The results obtained are not conclusive. It can be seen from the stereogram (fig. 6) that there is reasonably close agreement with the low-temperature curves. The (010) curve is much shortened towards the anorthite end, and although there is some evidence that the composition-plane readings show a greater variation in An than the twin-plane readings, the points are too crowded together for any differences to be significant. Results from the other curves are more interesting. The [001] values for the twin-plane curve can be compared with the (001) values for the cleavage: the former show only a 4 % variation in composition; the latter about 25 %: the change in composition here is across a (001) twin plane, not as before an albite twin plane. It would be interesting to investigate high-temperature plagioclases with An_{75}, for on such evidence as is available it seems likely that they would show a similar inhomogeneity to that found towards the albite end of the series. Here again it might prove possible to deduce something of the thermal history of the rock from the composition variation in the crystal.

Refractive-index measurements.

The Norwegian workers reported that universal-stage measurements with high-temperature felspars gave incorrect anorthite percentages, and such measurements should clearly be checked by some other independent method. Since crystals from the same rocks may vary in composition, a chemical analysis—which is necessarily a bulk analysis of many crystals—was felt to be inadequate. Refractive-index measurements performed on single crystals are not open to the same objection. The method finally adopted used a thin section of slightly more than standard thickness (about 0·035 mm.). A suitable felspar—where possible one showing maximum birefringence—was then cut out of the section, and the extreme indices $n_{\alpha'}$ and $n_{\gamma'}$ were measured on a selected part of the crystal edge by the standard immersion technique. The crystal was then remounted and examined on the universal stage. This method has a number of disadvantages: the crystal tends to break up before it is remounted; a more serious objection is that refractive-index measurements are necessarily made on the crystal edge, while universal-stage measurements are made at some distance within the crystal. This must give rise to a discrepancy in any zoned crystal. A further source of error is in the extrapolation from the measured values $n_{\alpha'}$ and $n_{\gamma'}$ necessary to obtain the values for n_α and n_γ (or possibly n_β). The refractive-index variation diagram of Emmons (19) was used for extrapolation; the results are, of course, most accurate when n_α and n_γ are nearly in the horizontal plane of the crystal section—i.e. when the crystal shows maximum birefringence. Because of these complicating factors, it was thought sufficiently accurate to measure the refractive indices of the crystal in white light; the refractometer used was compensated to give the Na-light value. Each index was measured at least three times.

Table I compares the anorthite values found by the two methods. The composition has been calculated from the refractive indices using both the empirical graph given by Chudoba (20) and the amended version proposed by Chayes (21), although to simplify the table the Chayes values are given only in the final column. The difference between the two sets of values is generally less than 2 %. The two curves diverge most over the albite range (An_{0-10}) and for the more basic felspars ($An > 60$). In this latter region Chayes has been able to incorporate new and much improved data. In dealing with the intermediate felspars he has had to rely more on results culled from the literature over the past fifty years. Those results that are clearly improbable have been rejected, but more really accurate determinations are still required. The correspondence between the two curves in this intermediate region may be due to the fact that many of the same determinations were used for both, and this part of Chudoba's graph may still require minor modifications.

The refractive indices measured are quoted to the fourth place. This is justified in view of the reproducibility of the measurements—it is one of the advantages of this method that determinations can be repeated on the same crystal as often as required—and the probable error (calculated on the standard square-root formula) was greater than 0·0003 in only 5 of the 58 determinations recorded here. This is not, of course, the same thing as claiming an absolute accuracy of this order, but, as conditions were standard throughout, the relative accuracy is adequate for purposes of comparison.

In the last column of the table the two sets of values are compared. In addition to the individual comparisons, the mean difference for the two methods for all the crystals from one rock is given. It is at once clear that the Brodick plagioclase is markedly different from the other material. The refractive-index results are consistently lower—as the Norwegians also found with high-temperature felspars—and this strongly supports the view that these are high-temperature forms. It is more difficult to explain why three of the other four rocks show a constant mean difference of about 4% An between the two sets of values. It seemed possible that this discrepancy might be inherent in the experimental method used—and this was, in fact, found to be the case. A number of refractive-index measurements were made on these felspars in white light and were repeated using Na-light. In all cases the white-light values were lower, the difference being equivalent to about 4–5 % anorthite (range 0·0022–0·0028). The selection of the end-point when matching crystal and liquid is of course more subject to personal factor when white light is used, but the extent of the variation is not

TABLE 1. Plagioclase composition determined by two optical methods.

The numbers in column 1 refer to the crystal and, in brackets, to the sub-individual measured.

		Refractive-index measurements						
		n_α.	% An.	n_β.	% An.	n_γ.	% An.	% An mean.
Olivine-gabbro, Stonehead, Aberdeen.	1 (1)	—	—	1·5566	49	1·5599	46·5	48
	3 (1)	1·5500	42·5	—	—	1·5594	45·5	44
	5 (1)	1·5526	47·5	—	—	1·5599	46·5	47
	6 (1)	1·5530	48	—	—	1·5605	48	48
	8 (1)	—	—	1·5545	44	1·5606	48	46
Hornblende-pegmatite, Ronez, Jersey.	1 (1)	1·5537	49	—	—	1·5635	53	51
	2 (1)	1·5517	45	—	—	1·5592	45	45
	2 (4)	1·5384	21	—	—	1·5452	19	20
	3 (1)	1·5342	14	—	—	1·5428	14	14
	3 (2)	1·5319	11	—	—	1·5450	17·5	13·5
	4 (1)	1·5334	13	—	—	1·5431	14	13·5
	5 (2)	1·5345	14	—	—	1·5434	15	14·5
	5 (3)	1·5437	28	—	—	1·5503	28	28
Felsite, Glen Cloy, Arran.	1 (3)	1·5496	41	—	—	1·5594	45	43·5
	2 (1)	—	—	1·5531	41·5	1·5569	41	41
	4 (1)	1·5455	34	—	—	1·5525	32	33
	5 (3)	1·5468	36	—	—	1·5538	34	35
	6 (1)	1·5464	35	1·5501	35	—	—	35
Pitchstone, Tenerife, Canary Is.	1 (1)	—	—	1·5528	41	1·5572	41	41
	2 (1)	1·5501	42·5	—	—	1·5577	42	42·25
	3 (1)	—	—	1·5508	37	1·5551	37	37
	4 (1)	1·5478	38	—	—	1·5561	39	38·5
	7 (1)	1·5473	37	—	—	1·5564	40	38·5
Porphyritic pitchstone, Brodick, Arran.	1 (1)	1·5364	18	—	—	1·5478	23	20·5
	2 (1)	1·5366	18	—	—	1·5434	14	16
	4 (1)	1·5368	18·5	—	—	1·5452	19	18·75
	5 (1)	1·5405	24·5	—	—	1·5470	22	23·25
	6 (1)	1·5346	14	—	—	1·5440	15	14·5
	7 (1)	1·5375	20	—	—	1·5449	17·5	18·75

always appreciated; in this case the matching point has been that of green light (it should of course be constant for any one observer). The strong zoning of the Ronez plagioclase makes any close agreement between the two sets of values unlikely.

Fig. 7 shows some results plotted on the Köhler curves of twin-pair angle against composition. The values are for albite and Carlsbad twin pairs for crystals from four of the rocks (the Ronez plagioclase was not

TABLE I (*continued*).

Universal-stage measurements (% An)						Universal-stage values minus refractive-index values.			
Composition plane		Twin plane				Composition plane		Twin plane	
(010).	Pericline.	(010).	(001).	⊥(001) in (010).		Chudoba.	Chayes.	Chudoba.	Chayes.
54	—	—	—	—		+6·0	+7·0		
47	—	—	—	—		+3·0	+3·0		
55	—	—	—	—		+6·0	+6·0		
49	50	—	—	—		+1·0 / +2·0	+1·0 / +2·0		
50	—	—	—	—		+4·0	+4·5		
					mean	+4·5	+4·5		
48	—	—	—	—		−3·0	−3·0		
40	—	—	—	—		−5·0	−5·0		
24	—	—	—	—		+4·25	+4·75		
13	—	—	—	—		−1·0	+1·0		
17	—	—	—	—		+3·25	+4·0		
14	—	—	—	—		+0·5	+2·25		
20	—	—	—	—		+5·5	+7·5		
32	—	—	—	—		+4·0	+3·0		
					mean	+1·0	+2·0		
44	—	—	—	—		+0·5	+0·5		
44	—	—	—	—		+3·0	+2·75		
41	—	41	—	—		+8·0	+7·5	+8·0	+7·5
42	—	—	—	—		+7·0	+6·5		
42	—	—	—	—		+7·0	+7·0		
					mean	+5·0	+5·0		
43	—	—	40	—		+2·0	+1·5		
43	—	42	—	37		+0·75	+0·25	−0·25, −5·25	−0·75, −5·75
45	—	—	42	—		+8·0	+7·75	+5·0	+4·75
42	—	—	42	—		+3·5	+3·0	+3·5	+3·0
45	—	—	42	—		+6·5	+6·0	+3·5	+3·0
					mean	+4	+3·5	+1·5	+1·0
34	—	—	—	—		+13·5	+14·0		
—	29	—	—	—		+13·0	+13·25		
31	—	35	—	—		+12·25	+13·5	+16·25	+17·5
37	—	30	—	—		+13·25	+14·25	+5·75	+7·25
34	—	30	—	—		+19·5	+20·25	+15·5	+16·75
29	—	—	—	28		+10·25	+11·25	+9·25	+10·25
					mean	+13·5	+14·5	+12·0	+13·0

suitably twinned). The curves $\alpha\alpha'$ and $\gamma\gamma'$ refer to the angles between the indices for the two individuals of an albite twin; $\alpha_1\alpha_2$ and $\gamma_1\gamma_2$ to the corresponding angles for the two parts of a Carlsbad twin. For the Stonehead gabbro crystals the value used for the composition was the mean of all refractive-index determinations; for the other three rocks the twin angles and composition were measured in each case on the same crystal: for all results the values were adjusted for sodium-light. The

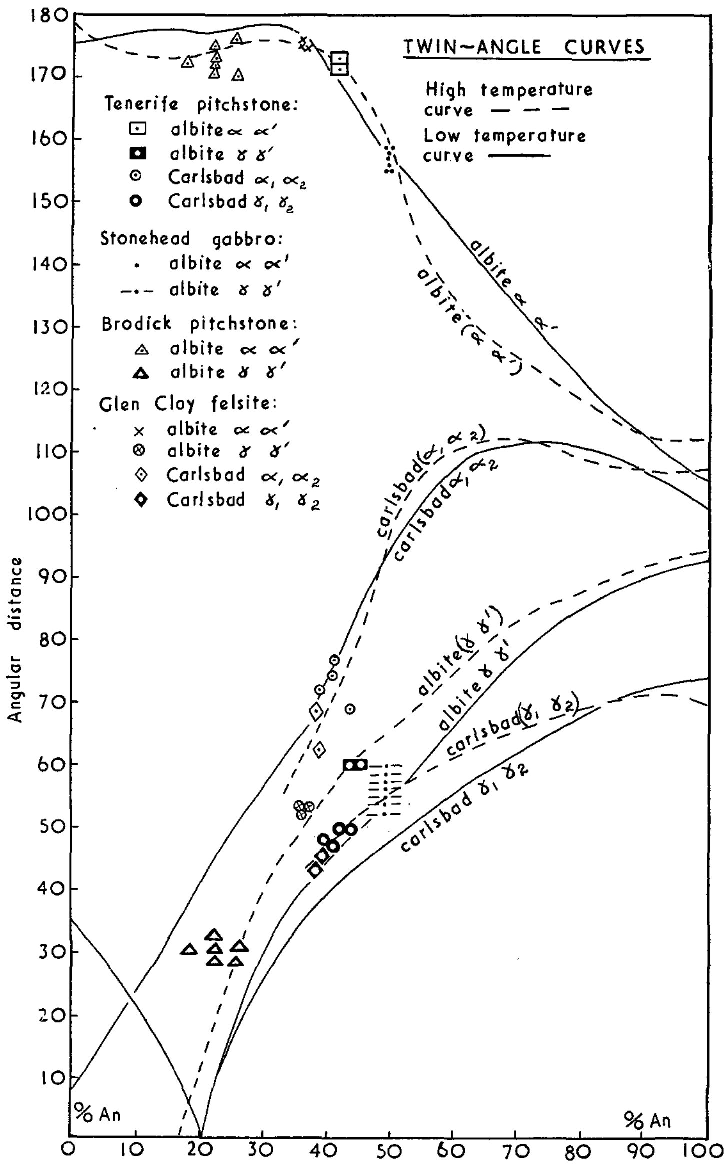

FIG. 7. Albite and Carlsbad twin-angles plotted on the Köhler high-temperature graphs.

results are highly interesting, but not always conclusive. The variation in optics between crystals from one rock is of the same order as the angular difference between the two curves, and it seems that it would generally be unwise to base conclusions about optics on one or two measurements only. The results may be summarized:

Stonehead gabbro.—Albite $\alpha\alpha'$ twin-angles fall at a point where the curves cross, those of $\gamma\gamma'$ extend from the low-temperature curve towards the high-temperature curve.

Tenerife pitchstone.—Albite $\alpha\alpha'$ and $\gamma\gamma'$ are high-temperature. Carlsbad $\alpha_1\alpha_2$ are apparently low-temperature (the two curves are close together at this point); $\gamma_1\gamma_2$ are high-temperature.

Glen Cloy felsite.—Albite twin-angles. $\alpha\alpha'$ are indeterminate, $\gamma\gamma'$ high-temperature. Carlsbad values are indeterminate. These felspars are so decomposed that it was difficult to obtain sufficiently accurate values; nevertheless there is again the general similarity between the Glen Cloy and Tenerife crystals that has been commented on before.

Brodick pitchstone.—The albite twin-angles are clearly those of high-temperature felspars. Here again there is more variation in optics between crystals than is desirable—in this case the difference in composition between adjoining albite twins undoubtedly contributes in part to this variation.

Conclusions.

High-temperature felspars have anomalous optics which may be recognized in at least three ways: twin- and composition-planes diverge from the standard Reinhard stereograms; composition determined from universal-stage stereograms differs from that given by refractive-index determinations; twin-angles fall on or near the high-temperature graphs of Köhler. It is probably unwise to rely on any one method exclusively. The Brodick pitchstone plagioclase is shown as high-temperature by all of these methods. The Stonehead gabbro, Ronez pegmatite, and Bushveld norite contain low-temperature crystals. The type of plagioclase from the Glen Cloy and Tenerife rocks is more difficult to ascertain. Crystals from both show a systematic displacement from the Reinhard curves and the Köhler twin-angles fit the high-temperature curves fairly adequately; on the other hand, there is no systematic difference in composition values obtained by different methods. It appears highly probable (from the X-ray work) that the distinction between high- and low-temperature plagioclase is brought about by an order-disorder transformation. The high-low albite relationship is believed to be an

Al–Si order-disorder; the anorthite end of the series (An_{72-100}) has Al–Si ordered throughout and the high-low changes are due to the disordering of some other group, presumably the cations. (This is in keeping with the larger optical differences between the high and low forms at the albite end of the series.) If this is the correct explanation of the high-low optics, then felspars in all states from the completely ordered low-temperature forms to the randomly arranged high-temperature forms will be found occurring naturally, the actual state of any given plagioclase being determined by its previous thermal history. The Glen Cloy and Tenerife crystals therefore show only partial disordering; the Brodick plagioclase is much more disordered—although even here the disorder is not necessarily as great as that found in an artificially prepared specimen. Alternatively there might be two types of disordering, only one of which shows the anomalous composition results.

It has previously been the custom to explain optical anomalies in the plagioclase series by the presence of other elements, notably potassium. There is no reason to doubt that the plagioclase lattice can tolerate a certain number of potassium atoms; it is not at all clear what effect this has on the optics, and it is hoped that it may prove possible to analyse the material from Brodick, Glen Cloy, and Tenerife to make sure that the optics have not been complicated by the presence of other elements. The variation in composition between adjoining albite twins is another factor which when it is better understood may be of value in interpreting conditions of petrogenesis. It is probably linked with the change from the albite-type to the intermediate-type structure. The particular composition at which this change in structure occurs may depend on the thermal history of the crystals.

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