THE PARAGENESIS AND OPTICAL PROPERTIES OF SOME TERNARY FELDSPARS

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The occurrence of ternary feldspars in slightly alkaline rocks is reviewed in the light of recent analytical data and views on the phase relations within the ternary system. The relationship between the optical properties, composition and structural state of these feldspars is also discussed and a new set of refractive index curves is presented; these have been drawn using data on the groundmass feldspars from hawaiites and mugearites.

Introduction

The term anorthoclase was first proposed by Rosenbusch (1885) in the second edition of his Mikroscopische Physiographie to include triclinic potash-soda feldspars previously known as soda orthoclase or soda microcline in which the cleavage angle differed scarcely or not at all from a right angle. These feldspars had already been grouped by Foerstner (1884) as "anorthic potash feldspars".

Except for the comparatively rare varieties containing barium or iron, the compositions of nearly all the natural feldspars can be expressed in terms of the three end members, orthoclase (Or.), albite (Ab.), and anorthite (An.); moreover, as there is very little solid solution between orthoclase and anorthite it is convenient to consider the chemical relationships of the feldspar group in terms of two major series, the alkali feldspars and the plagioclases. Except in alkali feldspars very rich in potash, and in calcic plagioclase, few analyses of the natural minerals are entirely devoid of the third component. In the potassic alkali feldspars the anorthite component is usually present in quite small amounts and may be neglected. In the plagioclase series however, small but important amounts of potassium are frequently present. Since the potassium contents usually reported rarely exceed two to three per cent of the orthoclase component, which in this amount appears to exert little influence on the optical properties, it is customary to neglect it also. However, as the sodic end of both the plagioclase and alkali feldspar series is approached an extensive field of ternary solid solutions is encountered. The presently known natural compositional limits of these ternary solid solutions are shown in Figure 1.

Experimental methods of determining phase relationships in the ternary field of the system $KAlSi_3O_8$–$NaAlSi_3O_8$–$CaAl_2Si_2O_8$ have suffered until very recently from the obstacle created by the impossibility of determining the ternary composition of a feldspar by X-ray methods.

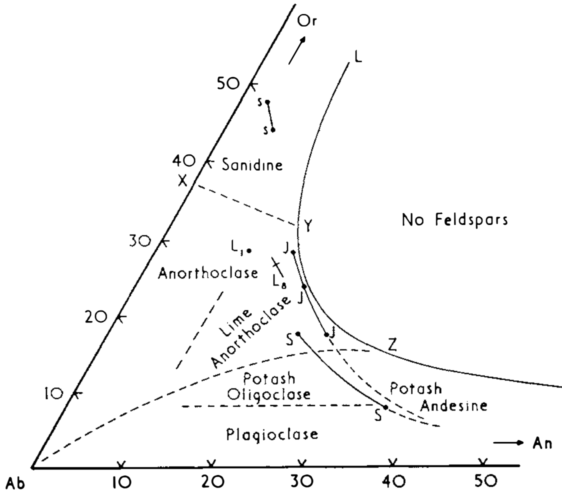

Figure 1. Plot of compositions in part of the ternary system $KAlSi_3O_8$–$NaAlSi_3O_8$–$CaAl_2Si_2O_8$ showing the maximum extent of solid solution in natural feldspars. The position of the ternary solid solution curve *LM* is taken from Tuttle and Bowen (1958, figure 64, p. 132) and the boundaries separating the fields of plagioclase, anorthoclase, and sanidine, from Smith and MacKenzie (1958, Figure 1, p. 874).

S analysed feldspar fractions from mugearite, Scrogg's Hill.

J analysed feldspar fractions from mugearite, Jeffrey's Hill.

L_1, L_8 analysed feldspars from larvikite specimens 1 and 8 of Muir and Smith (1956).

Full lines on *S* and *J* indicate composition range determined by analysis, dashed lines indicate probable range of compositions of optically determined plagioclase.

Because of this it has been necessary to deduce the maximum extent of solid solution by collecting data on the analysed feldspars from trachytic rocks whose compositions approach most closely to that of the synthetic system. This method was used by Bowen and Tuttle (1958) to locate the curve *LM* of Figure 1; the phase relations for their equilibrium diagram (Figure 64 p. 133) were deduced similarly by using data in the literature on the compositions of the two coexisting feldspars and the host rock, or the groundmass in lavas. Compositions near the curve represent feldspars that have crystallized at high temperatures from relatively dry mugearitic or trachytic lavas. This point is illustrated nicely by data on the analysed fractions of feldspars from two mugearites believed to belong to separate laccolites from the Dunedin district New Zealand, those from Jeffrey's Hill and Scrogg's Hill (Muir and Tilley (1961) Table 6 Analyses 12a and 13 respectively). Although these rocks are closely similar in composition and both are closely matched by the type Skye mugearite from Druim na Crìche, nevertheless the pyroxene and feldspar compositions of the two are strongly contrasted. The Jeffrey's Hill rock is dense and fine grained and contains a relatively magnesian early crystallizing augite whereas the mugearite of Scrogg's Hill is relatively coarse grained; its pyroxene is a titaniferous ferroaugite that has crystallized late, appearing as narrow prisms in the interstices between the feldspar laths and it contains a significant amount of interstitial calcite. The feldspars from Jeffrey's Hill are zoned continously from a potassic plagioclase to lime anorthoclase showing the maximum extent of solid solution whereas the lime anorthoclases from Scrogg's Hill do not approach the curve *LM* so closely, and never become so potassic. They are accompanied however by a small amount of monoclinic soda sanidine occurring as discrete patches in the final residuum. It seems fairly certain that the Scrogg's Hill rock has crystallized over a range of considerably lower temperatures than that of Jeffrey's Hill. Another good example comes from Druim na Crìche itself where the groundmass feldspars from the upper, and earlier member of the composite sill, of hawaiite composition (Muir and Tilley unpublished data), are indicative of significantly higher temperatures than are those already reported for the mugearite itself where analcime occurs.

It is thought that the extent of solid solution in the dry system would be somewhat greater than has so far been found naturally and it is hoped that further light on this problem and on others in the ternary system will be forthcoming from the newly developed ion exchange method of controlling compositions in the one-feldspar field.

The field boundary *XY* of Figure 1 between sanidine and anorthoclase was determined by Smith and Mackenzie (1958) from natural and synthetic high-temperature feldspars; they found that specimens more sodic than $Or_{37}(Ab+An)_{63}$ remained triclinic when homogenized whereas more potash-rich specimens became monoclinic. They showed also that on further heating the boundary between the monoclinic and triclinic high-temperature sodium-rich feldspars migrates progressively towards the position of the line *Ab–Z* of Figure 1. This line marks the field boundary between anorthoclase and plagioclase, and separates the compositions of those homogeneous triclinic high-temperature feldspars which invert reversibly to monoclinic symmetry before beginning to melt from those which begin to melt before they acquire monoclinic symmetry.

Since monoclinic alkali feldspars do not usually contain more than five per cent of the anorthite component, and since normal rock-forming plagioclases rarely contain more than the same amount of the orthoclase component, it is convenient to regard any feldspar containing more than five per cent of the third component as a ternary one. The names most commonly applied to such minerals in present day petrographic nomenclature are anorthoclase, lime anorthoclase, potash oligoclase, and potash andesine. As will be shown, these minerals are common constituents in alkaline lavas especially as groundmass constituents. Their positive identification in the past has been hindered by confusing the influence of the orthoclase content of a plagioclase with that due to the normal high temperature form, and by difficulties unfortunately created by the concept of *anemousite*.

Although the name anorthoclase is familiar to most petrologists and conjures up ideas of the famous rhomb-shaped feldspars of some of the rocks of the Oslo area, the alkaline lavas of East Africa, and those of Mt Erebus, Antarctica, some of the other names also have a long history. The term potash oligoclase was first used by Iddings (1906, p. 322) to include triclinic feldspars (lime-soda microcline or anorthoclase) containing from three to five per cent of lime (15 to 25 per cent of anorthite). Even more calcic varieties have been described from alkaline Pacific lavas first by Barth (1929), (1931), and later by Macdonald (1942) as potash andesine. The term lime anorthoclase was introduced by Aoki (1959) to cover the feldspar found as microphenocrysts in the alkaline lavas of the Iki Islands and the Higashimatsuura district of Japan. This mineral has also been found by Muir and Tilley (1961) to be a prominent modal mineral in hawaiites and mugearites. It indicates a mineral lying in the anorthoclase field of Figure 1 that contains more than ten per cent of the anorthite component.

Morphology and twinning

When anorthoclase occurs as crystal lapilli or as phenocrysts in hypabyssal or volcanic rocks it frequently exhibits a very distinctive morphology. One variety, typical of some Oslo rocks, is distinctly stumpy while the other is distinctly elongated; both are characterised by a rhomb-shaped cross section. The crystals are nearly always zoned to some extent and exhibit more or less well developed $\{110\}$ and $\{\bar{2}01\}$ faces, sometimes with $\{\bar{1}01\}$ as well. Oftedahl (1948) has made the point that in the Oslo rocks, the crystal core about which the rhomb-giving faces of ternary feldspar are developed has always proved to be an oligoclase and that these faces never developed primarily on alkali feldspar crystals. According to Muir an Smith (1956) however, the central portions of most of the crystals in the larvikites represent stages in the unmixing of an originally homogeneous ternary feldspar; this is certainly the case for the Mt Erebus and Mt Kenya occurrences.

Anorthoclase characteristically displays a very finely developed crosshatched twinning on the albite and pericline laws; this is best seen on sections cut nearly parallel to (100). Sometimes in certain orientations, when the albite twinning is more coarsely developed in the central portions of the crystals, and where the feldspar is composed of slightly disoriented blocks, it may be confused with a primary oligoclase. In many cases this twinning becomes very much finer towards the margin of the crystal and eventually cannot be resolved optically although its presence can be detected by X-ray methods (Figures 2*a* and *b*).

In addition to the multiple twinning on the albite and pericline laws, a number of crystals are found as simple contact twins on the manebach, or more commonly, the carlsbad laws. In the lavas, the carlsbad twin occurs with the uncommon $\{100\}$ as composition plane

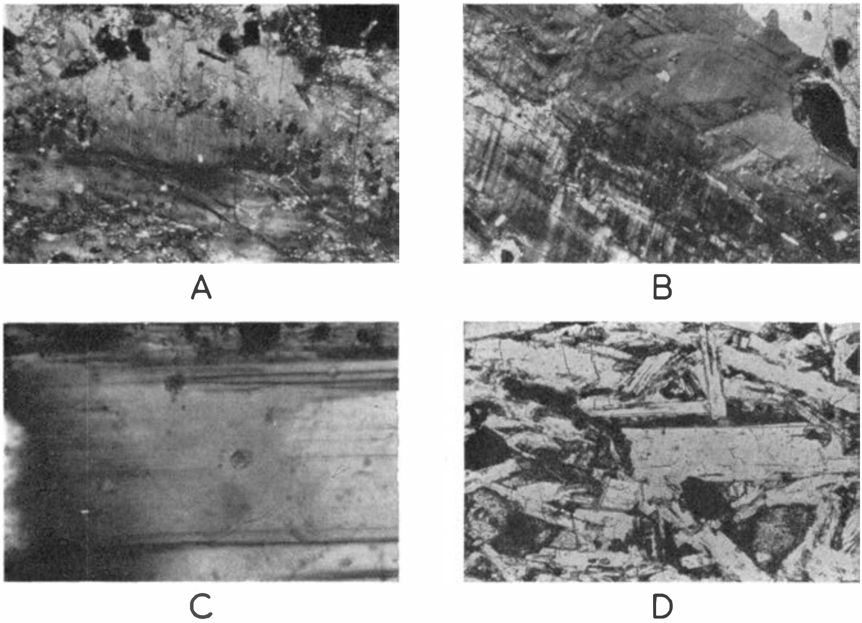

Figure 2. Microphotographs of ternary feldspars.

a) Portion of feldspar phenocryst from Rhomb Porphyry of Tyveholmen Dyke. The rather altered plagioclase antiperthite of the central part of the crystal shows albite and carlsbad crosshatched twinning. This grades outwards (in the upper part of the photograph) into a feldspar that shows finer twinning and this in turn is mantled by submicroscopically twinned anorthoclase.
Crossed nicols × 100.

b) Portion of large composite feldpsar crystal from Larvikite 8 (Muir and Smith 1956); the marginal portion of the crystal is in the upper part of the photograph.
Crossed nicols × 29.

c) Portion of feldspar microphenocryst from Mugearite of Scrogg's Hill, Dunedin district, New Zealand. Detail to show the twinning in the marginal portions of the "pseudoplagioclase". The central part of the crystal (right hand side of photograph) is a high plagioclase An_{42} that appears to be significantly potassic. This grades outwards through potash oligoclase and lime anorthoclase (moderately dark areas in central part) which shows very fine shadowy crosshatched twinning, to margins of anorthoclase (dark area on left). Note the persistence of coarser albite twin lamellae into the marginal parts of the crystal.
Crossed nicols × 590.

d) Photograph showing the same microphenocryst (large crystal in centre) of "pseudoplagioclase" with large fresh olivines and interstitial ferroaugite, iron ores and soda sanidine.
Plane polarized light × 100.

whereas in the plutonic representatives the composition plane always appears to be {010}. Normally it is a simple twin but Oftedahl (op. cit.) has described a few cases where carlsbad threelings, fourlings, and sixlings occur.

Although the appearance of these crystals is most spectacular when they occur as large phenocrysts, by far their most widespread occurrence is as a groundmass constituent of slightly alkaline lavas. Most of these feldspars appear to be completely untwinned but in a few cases careful examination on the Universal Stage can reveal fine shadowy and very diffuse crosshatched albite and pericline twinning with the rhombic section dihedral angle σ near $-3°$. The twinning becomes invisible when the composition planes are inclined at more than 3° from the normal to the section and hence, can easily be overlooked (Figure 2c). In some cases, where the ternary feldspar occurs mantling a plagioclase, the albite twin lamellae of the latter may persist into the anorthoclase mantle. Twinning of this type (Figure 2*d*), which must be regarded as growth twinning, is responsible for much lime anorthoclase being identified incorrectly as plagioclase. The difficulty is enhanced when the refractive index of the mantling feldspar is distincly greater than the mounting medium, usually Canada Balsam, $n \simeq 1.540$. Up to the present no detailed X-ray investigations have been carried out on these groundmass feldspars but they offer a promising field for further study.

Optical properties

Although the scope of optical methods is not nearly so complete in these feldspars as it is in the plagioclases, and the observations are hindered by the small grainsize and the presence of fine twinning, nevertheless the results of a detailed optical study can be used to obtain data of considerable value and the results will have greater significance if they can be supplemented by a detailed single-crystal X-ray investigation.

Just as the optical properties of the plagioclases vary with composition and structural state, so too do smaller but similar variations occur in the ternary feldspars. Here, however the variations in the orientation of the optical indicatrix are restricted by the much closer approach to monoclinic symmetry. Moreover, the significance of the observed variations is obscured in many cases by complications due to unmixing, and inversions in the unmixed or partly unmixed phases, and also by the presence of submicroscopic twinning.

In contrast to the plagioclases, comparatively little attention has been devoted in the past to investigating in a systematic way the orientation of the indicatrix in the alkali feldspars in general and the ternary feldspars in particular, because of the difficulties created by the widespead occurrence of fine twinning, their relatively low birefringence, the nature of the crystals in the groundmass of lavas and by the prevalence of chemical zoning. Nikitin (1936 Tafel VII) proposed a very tentative diagram for the optical orientations of the alkali feldspars (Figure 3*a*) and its use has been discussed by Oftedahl (op. cit.) and more recently by Marfunin (1961*a* and *b*). Marfunin pointed out that in the past such Universal Stage measurements as had been recorded on the alkali feldspars did not attain the requisite accuracy and showed that reproduceable results could only be obtained by applying conoscopic methods to specially prepared sections of large crystals of high optical quality, cut nearly normal to the x-crystallographic axis, ground flat and then polished. He determined the angles between the plane of the section and each of the cleavages by means of a one-circle goniometer, cemented the polished surface of the specimen to the slide, and finally reduced the thickness to the order of 0.05 to 0.10 mm. His Universal Stage observations were carried out using a × 40 objective of comparatively low numerical aperture

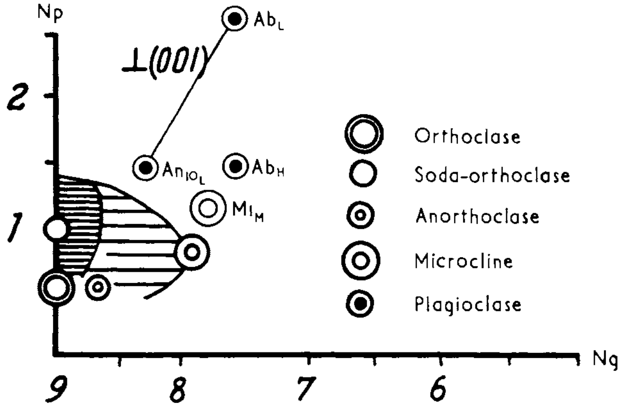

Figure 3a.

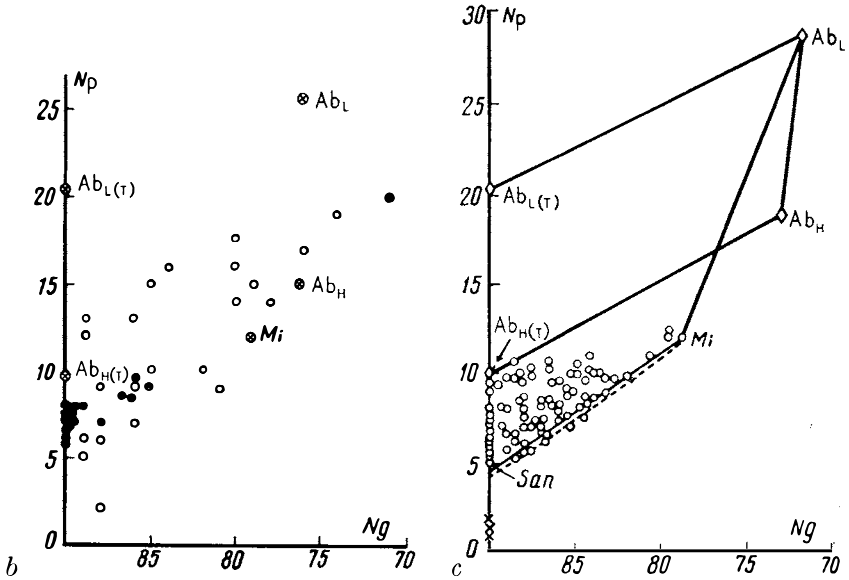

Figure 3. Optical orientation diagrams for triclinic feldspars

a) Nikitin's diagram (1936 Tafel VII) showing the position of the (001) pole with respect to fixed optical vectors as drawn by Oftedahl (1948 Figure 20). The heavily hatched area indicates the variation field of the nearly monoclinic feldspars; the lighter hatching refers to the triclinic feldspars. The points for high and low albite are taken from Marfunin's data (1961a).

b) Marfunin's diagram (1961a Figure 1) showing measurements on potash feldspars from the Elduhrtinsky Granite. Open circles indicate measurements by orthoscopic methods. Closed circles indicate measurements by the conoscopic method in goniometrically oriented plates. Crossed circles, points for microcline (Mi), low albite (Ab$_L$), high albite (Ab$_H$) and their submicroscopically twinned equivalents; Ab$_{L(T)}$ and Ab$_{H(T)}$.

c) Marfunin's diagram (1961a Figure 2) showing the results of his universal stage measurements on potassic alkali feldspars using specially oriented specimens and the conoscopic method.

in conjunction with a special condenser and normal 11.5 mm. radius hemispheres. This method, a development of that recommended by Smith and MacKenzie for the determination of $2V$, can unfortunately, only be applied to the study of large crystals. The validity of Marfunin's conclusions concerning the accuracy of his measurements is immediately evident from Figures 3*b* and *c*.

Petrologists have usually relied on optical methods of symmetry determination but if a ternary feldspar is submicroscopically twinned or unmixed the optical symmetry may be quite misleading. Anorthoclase cryptoperthites may be either monoclinic or distinctly triclinic optically as shown by small extinction angles of from 1° to 5° in the zone ⊥ (010) and they tend to give highly variable results for the orientation of the indicatrix from one specimen to another and in some cases from one crystal to another of the same specimen. If the specimens are partly unmixed cryptoperthites, consistent results may be obtained by heating the specimens until the diffractometer traces show them to be homogeneous. Oftedahl (op. cit.) showed that such pseudomonoclinic crystals owed their character to the intergrowth of a monoclinic potash phase together with balanced albite-twinned soda feldspar components. Tuttle (1952) showed that after homogenization such crystals could produce consistently triclinic optics. This appears to be the case also with those groundmass feldspars of the hawaiites and mugearites which show no evidence of unmixing in their diffractometer patterns.

However, even if the feldspar is homogeneous the optical properties may be effected by the degree of order, and by the presence of submicroscopical twinning in domains related to each other by the albite law, by the pericline law, or by both. If the twinning is "balanced", i.e. equal amounts occurring in each of the two or four orientations, as might be expected from an originally monoclinic crystal, then the resultant symmetry will still be monoclinic. If the twinning is unbalanced then varying degrees of triclinicity may be shown.

Refractive indices

A number of investigators have correlated the relationship between the known variation in the refractive indices of the alkali feldspars and their chemical compositions with most emphasis being placed on determining the dominant Or:Ab ratio. Tuttle (1952) showed that if the lime content of the feldspar was disregarded, whereas the α and γ refractive indices varied sympathetically with the structural state and γ showed the greatest variation, the β refractive index hardly varied at all. Since the total change in the value of β from Or to Ab is only 0.011, an accuracy of $\pm .001$ is required if the measurement is to be of any value and this can only be attained if careful attention is given to controlling the temperature.

Hewlett (1959) demonstrated that the replacement of Na for K has a greater effect on the vibration direction more nearly aligned with the y-axis (usually γ) than with that approximating to the z-axis (usually β), and that both of these were effected more than α. He also showed that the refractive index α, as in the plagioclases appears to be little effected by Al:Si order-disorder but increases slightly with the degree of unmixing. The refractive index γ shows the greatest relative differences because it is affected both by the degree of Al:Si order as well as by the extent of unmixing. For all four series of alkali feldspars β shows relatively little variation because the decrease in its value due to ordering is compensated for approximately by the increase due to unmixing. The process of homogenization produces a more open structure and hence a lower density and refractive index, but this applies only to cryptoperthites. When a soda-rich antiperthite is sufficiently coarse to be resolved optically a small decrease in refractive index should accompany homogenization because of the added potassium ions.

When calcium is present even in small amount its effect is to swamp the small increase in refractive index due to soda-potash replacement. This was recognised by Oftedahl (op.cit.) who acknowledged the importance of the anorthite component by plotting the refractive index variation on a ternary diagram; he used the function $\frac{\alpha+\gamma}{2}$ in order to eliminate the sympathetic variations in α and γ discussed above.

The optically homogeneous ternary feldspars appear to represent either a single phase that is submicroscopically twinned or else a cryptoperthite composed of one or more plagioclase phases and an alkali feldspar phase, all of which may be twinned. In the latter case the contribution of the plagioclase phases is likely to have a dominant effect on the refractive indices. Since the α refractive index of both alkali feldspars and plagioclases is little effected by the extent of Si:Al ordering, this has been used to construct the refractive index curves shown in Figure 4. The α refractive index has an additional advantage in that it can readily be determined to a close approximation from either a {001} or {010} cleavage flake in sodic plagioclases or alkali feldspars; this is a great advantage when working with groundmass feldspars. The use of the α refractive index alone merely enables an

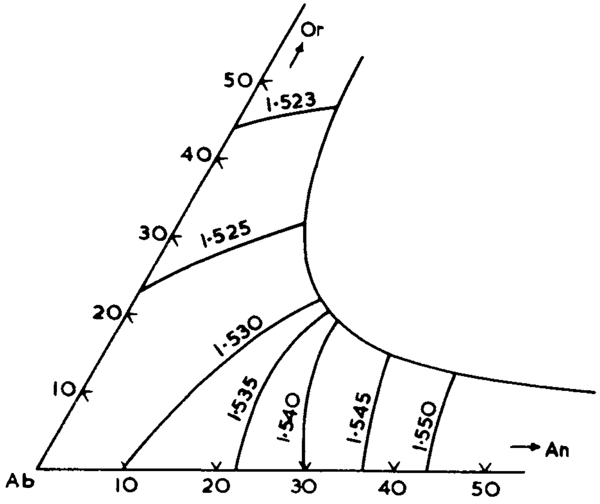

Figure 4. Tentative diagram showing the relationship between the α-refractive index and composition for feldspars from hawaiites and mugearites.

estimate to be made of the composition range and requires the use of some other optical variant to fix the composition.

Optical orientation

As we have seen the ternary feldspars occur either as crystals that appear to be homogeneous but are submicroscopically twinned, or as block crystals that are partly or completely unmixed; in both cases composite optics result. In the plagioclase series the influence of the potash content on the optical orientation was investigated by Chudoba and Engels (1937) who concluded that the optical orientation was not significantly effected but that there was evidence that the entry of potassium produced quite a strong variation in the size of the optic axial angle. These conclusions were borne out by Barth's observations (1931) and by those of Macdonald (1942). Barth had described as possible anemousite the groundmass feldspars from rocks now known as hawaiites from the Central Pacific. These feldspars were optically positive, had variable but large optic axial angles and had refractive indices that would place them in the andesine-oligoclase range. Similar feldspars in the calcic andesine range but with apparent small positive optic axial angles have been described by Sugi (1940) from an olivine dolerite from Fu-shun in Manchuria. He was able to show that in this case the optical properties were caused by the superposition of two thin plates of feldspar with {010} approximately parallel and related probably by twinning on the carlsbad or albite laws. Such crystals were found to consist of two parts in which the orientations of the α vibration direction were nearly opposed. As the abnormal properties were restricted to the overlapping areas it was concluded that they were the result of partial compensation of the birefringence in one layer by the other layer in a nearly opposite orientation.

Similar potassic feldspars have been described by Aoki (1959) who was unable to find any with low positive optic axial angles but did note that the optic axial angles of the potash oligoclases were slightly smaller than those of high plagioclase. The feldspars described by him graded out into lime anorthoclase and thence into anorthoclase. Muir and Tilley (op. cit.) showed that only after the plagioclase became more sodic than An_{30} did the potash content begin to have a significant effect upon the optic orientation and at this stage the feldspars entered the composition field of lime anorthoclase.

Marfunin (1959) in discussing the optical properties of the alkali feldspars (including anorthoclase) considered that they could be divided into two groups; the more structurally sensitive properties including the optical orientation and the size of the axial angle; and the less structurally sensitive properties including the refractive indices and the birefringence. He also considered the effect of submicroscopic twinning on the resultant optical properties of block crystals and showed that if the twinning is balanced the twin plane becomes an optical symmetry plane and the twin axis a diad axis of optical symmetry. With these relationships the minimum possible optical symmetry is monoclinic and as a special case when any two equivalent optical symmetry axes become parallel in each half of the twin, orthorhombic symmetry is produced. Submicroscopic twins can belong only to these two optical symmetry groups.

He then showed that by applying Pockel's formulae (1906) it was possible to calculate the three refractive indices, and hence the $2V$ of submicroscopically twinned crystals if the optical properties of the untwinned crystals were known. In pseudo-orthorhombic twins the symmetry axes of the resultant optical indicatrix must coincide with the "morphological symmetry axes". In pseudo monoclinic twins one axis of the resultant indicatrix must coincide with the diad axis of the twin and the other must lie in the plane normal to this. Here they may be determined by applying the Biot-Fresnel construction using the circular sections instead of the optic axes. Once the orientation of the resultant indicatrix and size of the optic axial angle has been determined, extinction angles may be calculated for different directions in the usual way.

As an example Marfunin showed that the resultant optical properties of a submicroscopic albite twin of Rischuna alibte (An_4) would have $2V\gamma = 86°50'$ and an extinction angle on (010), $\alpha' \wedge (001)$ of 20.5° whereas the actual values obtained by Barth (1929) from a monoclinic submicroscopically twinned albite from Zeeland of composition An_4 were $2V\gamma = 88°$, extinction angle on $(010) = 18°$.

Similar calculations on other feldspars showed that although considerable changes could be expected in the size of $2V$ and in the optical orientation between untwinned and submicroscopically twinned sodic alkali feldspars, only small changes should be produced in the potash-rich minerals. These calculations of course cannot take into account the effect of strain which must always be present in such block crystals but since Marfunin's measurements on such crystals agree closely with the calculated optical properties, it seems unlikely that strain can exert a large influence on the orientation of the indicatrix although it may be able to effect $2V$.

Since it is clear that all volcanic lime anorthoclases develop a very fine crosshatched twinning which is just visible in the case of the phenocrysts and is submicroscopic in the case of the groundmass, the twinning in this case would appear to exert a constant influence on their optical properties and hence is a factor that could be neglected in comparing the optical properties. Although these feldspars appear to consist of a single phase, all or some may be cryptoperthites. If the crystals really represent cryptoperthites then their lime content is sufficient to enable an intermediate plagioclase to exsolve at an early stage. In their study of the larvikite feldspars Smith and Muir (1958) were able to show that the coarseness of unmixing was related not only to the rate of cooling but also to the composition. They suggested that under similar conditions of crystallization the coarseness of unmixing of these ternary feldspars might be controlled by the same factors as determine the peristerite solvus. If the optic axial angles of

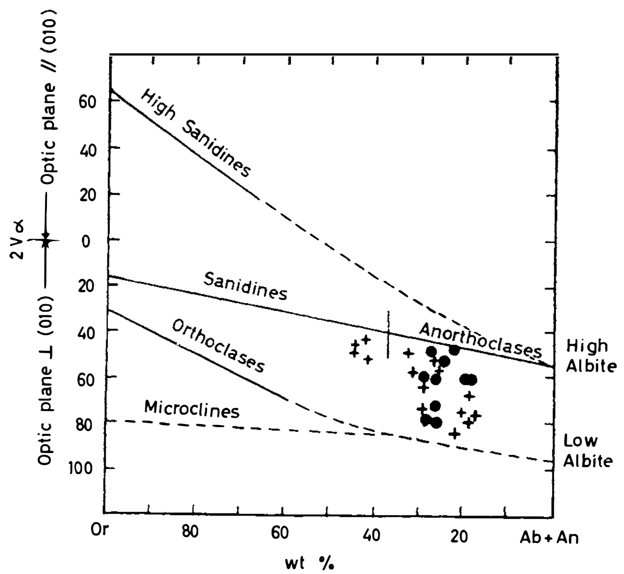

Figure 5. Optic axial angles of lime anorthoclase of Aoki (1959) and Muir and Tilley (1961) plotted on Tuttle's (1952) diagram.

● data by Aoki

+ data by Muir and Tilley

these volcanic ternary feldspars are plotted on Tuttle's (1952) diagram (Figure 5) they show consistently higher values of $2V_\alpha$ than do alkali feldspars of similar compositions but with smaller lime contents. This effect may be attributed to the presence of the calcium ion; alternatively it may be correlated with the presence of a lime-bearing plagioclase as a dominant component of the cryptoperthite.

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