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A contribution to the study of moonstone from Ceylon and other areas and of the stability-relations of the alkali-felspars.

(With Plates XIII–XV.)

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CONTENTS.

1. INTRODUCTION.

CEYLON moonstone is probably the best known variety of those alkali-felspars which display a prominent internal colour reflection or 'schiller'. On account of its blue sheen and its clear transparency, the mineral has attained a certain degree of popularity and some value as a gem-stone.

O. B. Bøggild (3)[1] has recently proposed the name 'labradorization' for this property. He suggests that none of the older terms,

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[1] Numbers in parentheses after authors' names refer to the list of papers on pp. 364–5.

schiller, lustre, &c., is sufficiently exclusive for the special types of internal colour reflection shown by the felspar group. While it is true that the felspars as a class display this property in a special manner, there are marked differences, as Bøggild himself points out, between the internal colour reflection of the alkali-felspars on the one hand and of the soda-lime-felspars on the other. It is open to question, for example, whether the relatively quiet sheen of moonstone and the brilliant hues of labradorite are produced by the same cause. For this reason, I use the older term 'schiller' to denote the property in the moonstones described in this paper.

Investigations into the cause of schiller in felspars have generally included the examination of specimens of Ceylon moonstone. But, unfortunately, in no case does the exact field derivation of the specimens examined appear to have been known. Except for the brief notes of A. K. Coomaraswamy (8, 9, 10) on the moonstones of the Kandy district, little published information is available regarding the occurrence and field-relations of Ceylon moonstones.

A few years ago I had an exceptional opportunity of carrying out a detailed examination of a china-clay property near Ambalangoda, in south-western Ceylon, from which moonstones were being mined. The property was situated on a rotted or partly-kaolinized pegmatite intrusion. Owing to the softness of the rock and the relative ease with which the undecomposed portions of the felspar (moonstone) could be separated by washing away the clay, the mine had become the chief source of supply for Ceylon moonstone, which previously had been obtained mainly from the Kandy district.

Samples of fresh moonstone and of felspar in various stages of decomposition were collected from this mine. These samples have been examined microscopically and chemically. The results of the investigations are given in the following pages, together with an account of the field-relationships of the mineral.

2. Occurrence and Field-Relations of the Moonstone.

The mine from which this moonstone felspar was obtained occupies the central portion of a rectangular area of swampy ground near the coastal village of Ambalangoda. The positions of the swamp and moonstone mine property are shown on the accompanying map (fig. 1), which has been derived from Sheet No. O/12, 4 B, of the Ceylon Government Survey.

The maximum width of the swamp is about half a mile and the length about two miles. From the results of hand-borings which I put down in 1922 over various parts of the swamp, it would appear

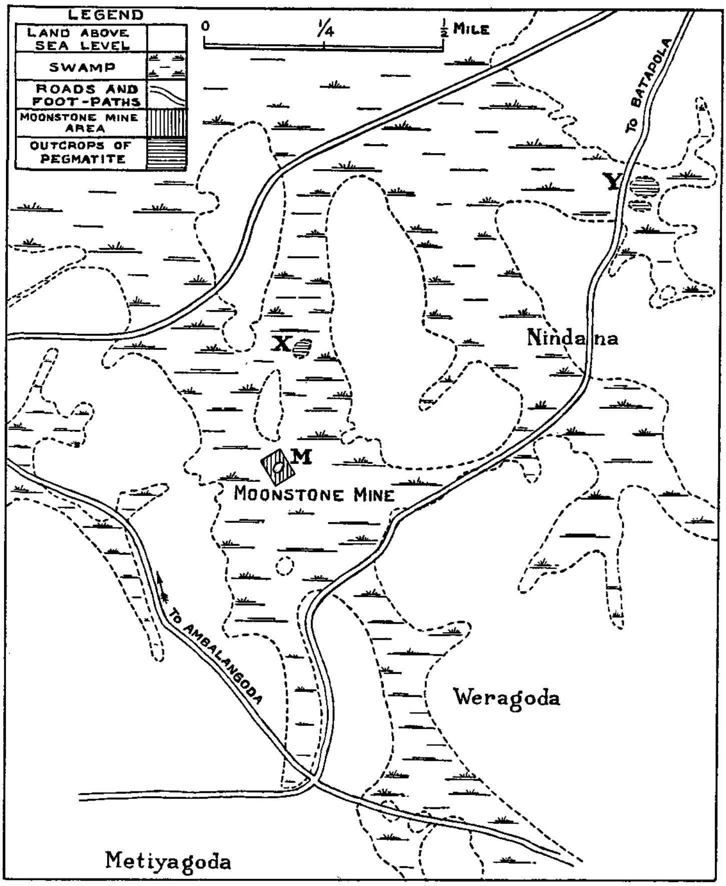

FIG. 1. Map of the moonstone mine area, Ambalangoda, Ceylon.

that rotted pegmatite-rock (china-clay-rock), similar to that obtained from the mine, underlies the greater part of the swampy area and is covered by an overburden of peaty vegetation, which varies from 4 to 20 feet in thickness.

The rising ground to the east and west of the swamp is under cultivation, producing cinnamon, coco-nut, and rubber. The soil tends to be hard and lateritic, with here and there outcrops of black felspathic gneiss or granulite, apparently the original country-rock of the pegmatite intrusions.

Two or three small islands or 'duwas' occur within the swamp. The soil of these is also hard and lateritic, but no exposures of solid rock were observed on them. The moonstone property lies near the centre of the swamp, a little to the south of one of these islands (see area M on map). Fragments of moonstone were first discovered near this island by the rice cultivators about 25 years ago.

The property was examined in 1906 by J. Parsons (24) of the Ceylon Government Survey, and the following is an abstract of his report:

> The moonstone is obtained by sinking pits in the swamp through about 4½ feet of black mud, when white kaolin is found. This is washed in baskets as in ordinary gemming operations and the moonstone is picked out of the material after the kaolin has been as far as possible washed away. It is found mixed with quartz. It is therefore probable that the moonstone is obtained as in the Kandy District from rock in situ only here so decomposed that the material can be dug out and washed. The rock would appear to be a leptynite as in the Kandy District, but there are some large boulders in and near the swamp showing pegmatite veins with large orthoclase individuals.

Decomposition at Depth.—When I examined the property in 1922 the working level from which the rotted pegmatite was being mined had reached a depth of 85 feet below the level of the swamp. The consistency of the rock at this depth was about that of a soft clayey gravel. Washing tests on samples collected by me from this level gave approximately: clay 48; felspar (moonstone) 45; quartz and opaline silica 7 %; marcasite, a small but persistent quantity. If we accept the usual chemical equation for the decomposition of felspar to kaolin, the residual felspar in the above cannot represent more than 30 % of the original pegmatite-rock.

The shaft at one time appears to have been carried to a depth of 100 feet. The material showed approximately the same consistency and composition from near the surface to the full working depth reached. The relative proportions of blue and white moonstone were very variable and the best material did not appear to follow any determinable direction in the mine.

Trial shafts sunk in other portions of the swamp, in search of the more valued blue stone, had not met with any success, the wash-residues yielding mainly opaque felspar and felspar with white or pearly schiller. In some parts of the swamp, especially towards the south, a little flake-graphite was found scattered through the clay-rock. (It may be noted here that graphite is a fairly common constituent of granulites and veins in this region. Extensive workings for graphite occur a few miles south-east of the moonstone mine area, near the village of Hikkaddawa, in association with rocks which appear to be of the same age and type as those of the moonstone mine area.)

At one point about 400 yards from the mine, near the north-eastern edge of the swamp (point X on map), a small outcrop of solid rock proved on examination to be a coarse pegmatite containing opaque white felspar, clear quartz, a small quantity of decomposed ferromagnesian mineral, and a few scattered graphite flakes. This rock undoubtedly represents the original undecomposed pegmatite-rock of the swamp area. Exposures of fresh pegmatite were also found in an adjacent marsh about one mile north-east of the moonstone mine (point Y on map). The felspar of the latter exposures was found to be mainly microcline.

Cause of Decomposition.—The decomposition of the pegmatite appears to have been brought about, at least in part, by the action of meteoric waters charged with humic acids and soluble peaty matter. The conditions were probably strongly reducing, since all the iron present in the rotted rock of the mine occurs as marcasite. The decomposed rock, even at a depth of 80 feet below the marsh, is stained to a uniform brownish colour by organic matter, which disappears on ignition, leaving the clay pure white. As will be shown later, evidence exists to show that the initial stages of decomposition were caused by hydrothermal or pneumatolytic action.

Felspar Residues.—The bulk of the residue left after washing away the clay consists of loose masses and clear fragments of schillerized felspar, some quite fresh, others showing various stages of decomposition. They vary in size from about 3 inches diameter downwards.

The decomposition has proceeded mainly along the plane of schiller, with the result that the loose masses of felspar break readily along this plane into tabular or flaky fragments. Amongst the decomposed portions of the moonstone residues a number of soft white tabular fragments of what appeared to be kaolinized felspar were found. A microscopic examination showed them to be perthitic felspar from which the albitic component had been removed by partial leaching and partial kaolinization. These peculiar and interesting specimens have an important bearing on the relation between perthitic structure and the schiller in the undecomposed felspar. They are described in detail on pp. 308–15.

3. Description of the Fresh Moonstone Felspar.

A. *Megascopic Characters.*

Practically all the rough or uncut moonstone felspar of the wash-residues possesses a pitted or frosted surface due to superficial decomposition. To facilitate sorting at the mine, the felspar residues are immersed in water, when the 'colour' is readily seen. By cleaving and breaking away the outer layers, lozenges and tablets of clear schillerized felspar are obtained.

I made a systematic examination of a large quantity of this felspathic material in search of clear felspar devoid of schiller, but all the felspar examined was found to be schillerized, the colour varying from deep blue to silky white. A few pieces were observed to show variable schiller in different portions of the same specimen, but in the great majority of the fragments the schiller was uniform. A number of typical samples were selected for investigation. For convenience, these have been classified as follows:

(*a*) White moonstone (with silky to pearly white schiller).
(*b*) Bluish-white moonstone (with bluish-white schiller).
(*c*) Blue moonstone (with sky-blue to deep-blue schiller).

Crystal Faces.—No true crystal faces were observed on any of the felspar fragments. This is hardly surprising in view of the amount of decomposition suffered by the original pegmatite-rock. Many of the fragments showed ill-developed prism-faces and surfaces parallel to the schiller-plane, but these were obviously the result of decomposition.

Twinning.—Two or three specimens showing Baveno twinning were found. Decomposition parallel to the schiller-plane in the twin portions of these specimens has resulted in the development of a very flat re-entrant angle diagonally in front, and a corresponding obtuse angle at the back.

Cleavage.—Cleavage parallel to the basal pinakoid (001) is perfect in all the fresh moonstone examined. The cleavage surface is clear and glassy. Cleavage parallel to the pinakoid (010) is not nearly so perfect as that parallel to (001). It is least perfect in the blue stones and slightly better in the white and bluish-white varieties. The cleavage surface (010) in the white and bluish-white stones is dulled by numerous fine striations which make an angle of about 70° with the basal cleavage. These striations are coarsest in the silky white stones and become extremely fine in the bluish-white moonstone. In the blue stones these fine regular striations are not visible, but the cleavage tends to be slightly uneven or undulatory.

Colour by Transmitted Light.—A clean piece of blue or white moonstone, free from inclusions, looks almost clear and colourless when seen by transmitted light through parallel cleavage faces in the direction of the *b*- or *c*-axis. A thickness of about 1 inch yields only a faint yellowish tint. Seen through polished surfaces in the direction of the *a*-axis the stone has a turbid appearance with a distinct brownish-yellow tinge. The turbidity is most marked in stones with a white schiller.

Inclusions.—The greater portion of the otherwise clear moonstone is rendered useless for gem purposes by the presence of inclusions visible to the naked eye. These may have the form of thin lath-shaped lamellae or of flattened cigar-shaped cavities. The long axis of the inclusion is in each case parallel to the *c* or vertical axis of the felspar, and the flat surface of the inclusions lies in one of the crystallographic planes, (100), or more rarely in (010) or (001). The inclusions may occur singly, or in swarms with a regular parallel arrangement, when they resemble a shoal of minute fishes swimming in the clear mineral. The microscopic characters of these inclusions are described on p. 303.

B. *Microscopic Characters.*

Fine Microperthitic Structure.—Before proceeding with a detailed description of the microscopic characters of the moonstone I may say that all specimens of the white variety from this area show a fine, sharp, and very regular microperthitic structure under a moderate magnification (25 diameters). The structure is best seen on (010) cleavage-flakes, and is visible in ordinary light, if the illumination is suitably adjusted. It is much more clearly visible if the section is placed near its position of extinction under crossed nicols.

The microperthite is coarsest in the pearly white moonstone. In the bluish-white stones it becomes finer and less distinct. In the blue stones it is very faint, sometimes almost invisible even with optimum conditions of illumination.

W. C. Brøgger (**4**) has described a similar graduation of microperthitic structure down to submicroscopic dimensions in the schillerized felspars of the Norwegian syenites. For this submicroscopic variety of perthite he has suggested the name of cryptoperthite. The main difference between the Norwegian microperthite and cryptoperthite on the one hand and the structures seen in the Ceylon moonstone on the other consists in the much greater uniformity and regularity of the microperthitic structure in the latter.

Coarse Shadow Perthite. In addition to the microperthitic and cryptoperthitic structures described above, these Ambalangoda moonstones exhibit another form of perthitic structure which does not appear to have been hitherto observed in potash-soda-felspar.[1] This perthite, which is only definitely visible under crossed nicols, takes the form of a coarser 'shadowy' structure superposed on the finer microperthite or cryptoperthite and inclined at an angle of about 10° to the direction of the fine microperthite in sections on (010).

It will be shown later that this 'shadow' or 'lattice' perthite probably represents the first separation of a homogeneous mixed crystal into two phases not very different in composition, at a temperature not very much below the point of crystallization. This appears to have been followed at a later period and at a lower temperature by the separation of the fine orthoclase-albite lamellae of the microperthite and cryptoperthite. The two phases of the coarser 'shadow' perthite have each yielded the fine lamellae of orthoclase-albite microperthite, but in different proportions; hence arises the difference in the mean extinction position for each of the 'shadow' perthite components, a difference which is the cause of their visibility under crossed nicols.

Nomenclature.—In order to avoid confusion in the description and discussion of these different forms of perthite, I have designated, in the following pages, the fine regular variety of microperthite as (or, ab) microperthite or cryptoperthite. The coarser 'shadow' perthite will be referred to as (Or, Ab) 'shadow' or 'lattice' perthite. Similarly, when the individual components or lamellae of these

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[1] A. F. Rogers (26) has described a perthitic felspar which possesses some features in common with the above structures. The principal plane of perthite separation is in both cases the unit prism instead of the usual perthite plane. The perthite separation in the felspar described by Rogers appears, however, to have been much sharper, more complete and final, than in the coarse 'shadow' perthite separation of the Ambalangoda moonstone.

perthites are referred to, the orthoclase lamellae of the fine microperthite are termed (or) microperthite and the albite lamellae (ab) microperthite. The corresponding phases of the ‘ shadow ’ perthite are referred to as (Or) ‘shadow’ or ‘ lattice ’ perthite and (Ab) ‘shadow’ perthite respectively. It should be understood that the above terms are used for descriptive purposes only. I do not desire to add to the already confused nomenclature of the alkali-felspar series, but there appear to be no existing terms which would suitably describe the phases of the ‘ shadow ’ perthite.

A. N. Winchell (31) has suggested that the terms sanidine and adularia be reserved for the high-temperature and low-temperature forms of potash-felspar respectively, and that barbierite and albite be reserved for the corresponding forms of soda-felspar. He assumes that the high-temperature modifications (a) are monoclinic and that they form homogeneous solid solutions with each other. His nomenclature makes no provision for the existence of high-temperature mixed phases corresponding to the (Or, Ab) type.

H. L. Alling (2) has assumed the existence of high-temperature mixed phases in a speculative equilibrium-diagram for the solid portion of the potash-soda-felspar series, based on S. Kôzu's work (14–19) on the thermal examination of moonstones, &c.[1] He suggests the terms α, β, and γ for the various high- and low-temperature forms of potash-felspar and soda-felspar respectively, but these terms do not distinguish between homogeneous high-temperature solid solutions and separated high-temperature phases, such as the (Or, Ab) ‘ shadow ’ perthites.

It should be pointed out that the terms (Or) and (Ab) do not indicate any necessary similarity to ordinary orthoclase and albite, such as is understood in the case of the (or) and (ab) of the fine microperthite. The two (Or, Ab) phases separated mainly along the common prism-planes of the crystal and probably possess somewhat similar crystallographic and other physical properties. The terms (Or) and (Ab) are here used simply to indicate two high-temperature phases, one rich in potash, the other rich in soda. It will be evident that the original (Or) and (Ab) phases of the ‘ shadow ’ perthite now consist of aggregates of (or, ab) microperthite, each phase containing different amounts of (or) and (ab). The (Or, Ab) phases no longer

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[1] In addition to the papers listed, reference should also be made to Kôzu's paper on the optic axial angle of Eifel Sanidine, Min. Mag., 1916, vol. 17, pp. 237–252.

exist in their original condition in the moonstone, and their outlines are only discernible in sections as shadowy remnants, owing to the different proportions of (or) and (ab) in the two areas.

Both the (or, ab) microperthite and the (Or, Ab) 'shadow' perthite are best seen on cleaved fragments on the planes (010) and (001).

Cleavage-flakes on (010).—A thin flake of the pearly white variety of moonstone cleaved on (010) shows, in ordinary light and with moderate magnification (a ½ or ¼ inch objective is most suitable), a fine regular (or, ab) microperthite over the whole of the field of view. Plate XIII, fig. 1, shows a photograph of one of these cleavage-flakes magnified 185 diameters. Certain optimum conditions of illumination are necessary for the structures to be visible in ordinary light. A bright source of light must be used, and this should be 'stopped down' with the substage diaphragm in order to obtain maximum visibility. Even with the relatively coarse microperthite of the silky white stones, the structure may become indistinct or invisible if the illumination is not suitably adjusted. Similarly, the microperthitic structure is less evident in a section produced by grinding than in a cleavage-flake, probably because of the light-scattering effect of the ground surfaces. For this reason all examinations of these moonstones for microperthitic structure were made on cleaved flakes.

The (Or, Ab) 'shadow' perthite is only very faintly visible in ordinary light. Under crossed nicols, with the section near the extinction position, the fine (or, ab) microperthite can be seen much more distinctly than in ordinary light, and the (Or, Ab) 'shadow' perthite is also prominently visible.

Plate XIII, fig. 2, shows the appearance under crossed nicols of the specimen shown in ordinary light in pl. XIII, fig. 1. Both the (or, ab) microperthite and the (Or, Ab) 'shadow' perthite are plainly visible in this photograph. The faint line which runs obliquely across the picture is the trace of the basal cleavage. It will be observed that the individual lamellae of the fine (or, ab) microperthite make an angle of about 73° with the trace of the basal cleavage. The length of the lamellae or fibres is about 0·05 mm. and the thickness varies from 0·001 mm. downwards, being in most cases about 0·0005 to 0·001 mm.

The lenses of (Or, Ab) perthite have a thickness of about 0·01 mm. and an average length of 0·2 mm. They lie obliquely across the fine microperthite, making an angle of about 64° with the trace of the basal cleavage, but they repeatedly branch off in the direction of the fine (or, ab) microperthite.

Cleavage-flakes on (*001*).—Basal cleavage-flakes of white moonstone show, in ordinary light, the (or, ab) microperthite structure as fine short interlacing lamellae or fibres, mainly parallel to the trace of (100) but branching off at angles of about 30° and 20° to the trace of (100), corresponding to traces of the prism-faces (110) and (320) respectively.

Under crossed nicols (pl. XIII, fig. 3), the coarse (Or, Ab) perthite is much more prominently visible in (001) sections than the fine (or, ab) microperthite. It forms a lattice structure or meshwork of two sets of interwoven bands, each set polarizing in slightly different colours and inclined at an angle of 23° to the trace of (100), and consequently at 46° to each other.

The boundaries of these (Or, Ab) lamellae are not clear and sharp as in the case of the fine (or, ab) microperthite, and the way in which they interlace and fade off into each other makes it difficult to estimate their size with any degree of accuracy, but the average thickness of the lamellae may be taken as about 0·01 mm.

It would appear from these sections on (001) that the development of the fine (or, ab) microperthite lamellae along the direction of the *b*-axis has been interrupted at the boundaries of the coarse interlacing (Or, Ab) structure. The fine (or, ab) lamellae are much shorter than in the (010) section, and they tend to branch off into the prism directions (110) and (320). The thickness of the lamellae is the same as in (010) sections, i. e. about 0·0005 to 0·001 mm., and the average length is about 0·01 to 0·02 mm.

The shortening of the (or, ab) microperthite lamellae in the direction of the *b*-axis as compared with their length in a direction perpendicular to *b* in the perthite plane is explained if we assume that the (Or, Ab) perthite separation has already impressed an incipient prism structure on the mixed felspar crystal. The trace of the intersection of the unit prism (110) with the (or, ab) perthite plane of lamellation would be a lozenge, which may be taken as defining the boundaries of possible interference to growth of the (or, ab) lamellae. The long and short diagonals of this lozenge (perpendicular to and parallel to the *b*-axis respectively) are in the ratio of about 3·5 to 1. This is roughly the ratio of the length to the breadth of the microperthite lamellae as measured in sections on (010) and (001).

Blue-White and Blue Stones.—A cleavage-flake parallel to (010) of a blue-white stone shows, in ordinary light, the same (or, ab) microperthite as a white stone, but the structure is much finer, sometimes being almost invisible. With crossed nicols, both the (or, ab) microperthite and the coarse but fainter (Or, Ab) lattice perthite are distinctly visible, but both structures tend to be less distinct than in the white stones (pl. XIII, fig. 4).

In the deep blue stones, the (or, ab) microperthite is only very faintly visible, even under the best conditions of illumination. The (Or, Ab) perthite is distinctly visible in some blue stones, but it is almost invisible in others.

It is very probable that the presence of the fine (or, ab) microperthite and possibly the (Or, Ab) perthite in the bluish-white and blue moonstone would not have been suspected had not the relatively coarse structures, readily visible in the silky white moonstone, suggested a similar but finer structure in the bluish-white and blue specimens.

Previous investigations by workers on the schiller and other properties of Ceylon moonstone have usually been made on the blue variety of moonstone, and most probably on ground sections. In most cases these stones have therefore been described as free from inclusions and from indications of microperthitic or cryptoperthitic structures and other microscopic indications of heterogeneity (see, for example, Bøggild (3, pp. 19–21) and Kôzu (14)).

Many other apparently homogeneous schillerized alkali-felspars would probably show the above-mentioned microperthite structures, if examined under the following optimum conditions:

(*a*) With a cleavage-flake on (010) or (001), of uniform thickness, mounted in a medium of about the same refractive index and polarizing in colours corresponding to 400–700 $\mu\mu$.

(*b*) With direct sunlight or brilliant illumination, under a $\frac{1}{2}$ or $\frac{1}{4}$ inch objective, keeping the light rays parallel as far as possible.

(*c*) With the nicols crossed and the section at, or very near, the mean extinction position for the perthite.

Under these conditions nearly all the blue stones that I have examined showed the presence of the (or, ab) microperthitic or cryptoperthitic structure, although in many of the specimens the structure was too fine for the individual lamellae to be distinguished.

The visibility of the structures appears to depend on accentuating the difference in refrangibility and double refraction between the two sets of lamellae. With a higher magnification than that of a $\frac{1}{4}$ or $\frac{1}{6}$ inch objective the structure is not clearly seen. The photographs of microperthite illustrating this paper were all taken by direct arc illumination, no diffusing ground-glass plate being used.

Large Inclusions.—The large isolated inclusions referred to on p. 297 appear as thin lath-shaped lamellae or cavities. Their length is 10 mm. or less, and the breadth is 1 mm. or less. A section cut parallel to the plane of these inclusions, (100), shows them as narrow laths parallel to the vertical axis *c* with numerous branching lines or cracks which extend a short distance (0·2 mm.) on each side of the inclusion in the direction of the *b*-axis, after which they taper off in an oblique direction. In addition to these thin lath-shaped lamellae, numerous shorter cigar-shaped inclusions are visible. These vary in length from a few millimetres downwards, and are usually clear and devoid of branching cracks. Many of these inclusions are, in reality, very thin flat cavities, as can be demonstrated by taking fragments cleaved across the direction of the cavity and boiling them in strong dye solutions, when the dye penetrates for some distance along the cavity.

Under crossed nicols, the felspar in the region of an inclusion shows uneven extinction. An inclusion seen in section on (010) shows a narrow area on one side extinguishing at a higher angle than the felspar field, and on the other side a similar narrow strip extinguishing at a lower angle. If the breadth of the inclusion lies in the plane of section (as is the case with many of the cigar-shaped inclusions) the surface of the inclusion and the immediate neighbourhood show a fairly coarse microperthite running obliquely across the inclusion in the direction of the finer perthitic structure of the surrounding field.

Sections cut perpendicular to the length of these inclusions (that is, perpendicular to the *c*-axis) show under crossed nicols a peculiar polarization ‘ colour halo ’ in the neighbourhood of the cavity or inclusion. In the direction of the *b*-axis, the polarization colour is lowered for some distance on each side of the cavity.

Order of Separation of the Various Structures.—It was at first thought that the large inclusions or cavities described above represented solution cavities formed in the initial stages of decomposition of the moonstone. Against this view was the fact that the inclusions were often found scattered through the body of otherwise clear fresh moonstone. It was also observed, when the decomposed stones were being examined, that the main decomposition plane is the plane of the (or, ab) microperthite lamellation and not the planes (100) or (110), which are the planes containing the large inclusions and the (Or, Ab) 'shadow' perthite structures.

It would appear that the large inclusions represent mainly gas cavities separated at or near the period when solidification of the moonstone took place.

The relationship of the (Or, Ab) 'shadow' perthite to that of the (or, ab) microperthite (as seen under the microscope) indicates that the 'shadow' perthite was the first of the two to be formed. As will be shown later, this separation probably took place by 'exsolution'[1] from the solid felspar at a temperature not much removed from the point of solidification. The directions of separation do not appear to have been sharply defined, but the separation took place mainly along the planes (320) and (110). The (or, ab) microperthite separated later, at a lower temperature, into sharply defined lamellae along a new plane. This plane, which was found on further investigation to be coincident with the schiller plane and the plane of decomposition of the moonstone, will in future be referred to as the plane Δ.

Extinction on (010).—Under a sufficiently low magnification, such as that given by a 1 inch objective, a cleavage-flake on (010) extinguishes fairly uniformly. The mean extinction relative to the trace of the basal cleavage ranges from 10° to 11° (or 79° to 80°) for the various specimens examined, with the vibration-direction more nearly normal to (100) than is the trace of the basal plane. This extinction obviously represents the average extinction for the two sets of (or, ab) lamellae. With a high magnification, the extinction of the individual (or, ab) microperthite lamellae can be detected and measured approximately. One set (presumably the albite component) extinguishes at about 16°–17°, the other (probably orthoclase) extinguishes at about 6°. The two sets of coarser (Or, Ab) lenticles extinguish at approximately 8° and 13·5° respectively.

Extinction and Composition.—If the separation of albite and orthoclase in the (or, ab) microperthite represents complete exsolution, it should be possible, by a comparison of the average extinction-angle of the moonstone with the extinction-angles of the orthoclase

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[1] The term 'exsolution' was suggested by H. L. Alling (1, p. 222) to indicate perthite separations from solid phases as distinct from crystallization from liquid phases.

and albite components, to arrive at a rough estimate of the proportions of the two felspars present. Thus, if we take the extinction-angle of albite on (010) as 18° and that of orthoclase as 5°, the proportion of orthoclase present will be approximately given by X in the *equation*:

$$\frac{5X+18(100-X)}{100} = 10{\cdot}5, \text{ and } X = 58\ \%.$$

This figure is fairly close to the actual figure determined by analysis (p. 307).

Similarly, if the differences in the extinction of the two sets of (Or, Ab) 'shadow' perthite lenses are due to the different proportions of the (or, ab) microperthite components present in each set, then the approximate composition of the original phases of the 'shadow' perthite can be deduced from their present mean extinction-angles; thus if X equals the amount of (or) present in the (Or) phase, then

$$5X+18(100-X) = 100\times 8{\cdot}0, \text{ and } X = 77\ \%.$$

Similarly, with the (Ab) phase, if X is amount of (or) present in the (Ab), then

$$5X+18(100-X) = 100\times 13{\cdot}5, \text{ and } X = 34{\cdot}6\ \%.$$

It would thus seem that in the first separation of the (Or, Ab) 'shadow' perthite the two phases had the following approximate composition:

	Soda-felspar.	Potash-felspar.
(Or) phase	23 %	77 %
(Ab) phase	65	35

O. B. Bøggild (**3**) has endeavoured to show that a broad relationship exists between the extinction-angle on (010) and the chemical composition of six schillerized felspars from different localities. Curiously enough, the one prominent exception to the rule was Ceylon moonstone. For this felspar Bøggild obtained an extinction-angle of 10° 35′. His examination of published analyses of Ceylon moonstone showed two (Hintze and Doelter) with soda-felspar nil, the third (by K. Seto for S. Kôzu (14)) gave 23 % soda-felspar. As Bøggild pointed out, his extinction-angle corresponded to a much more sodic felspar even than Seto's analysis, and he suggested, in explanation of this, that Ceylon moonstone may be rather variable in composition.

It will be noted that Bøggild's extinction-angle from Ceylon moonstone lies near to those obtained by me for Ambalangoda moonstone, and it seems highly probable that his samples were derived from this locality. If this were the case the composition would correspond to the analyses given on p. 307, which are much nearer Bøggild's requirements for the extinction-angle, and the specimen would then come more into line with the rest of the felspars on his list.

Winchell (31) has also made use of Seto's Ceylon moonstone analysis (and an extinction of 10–11° recently supplied to him by S. Kôzu) in drawing up a curve for the adularia-albite series, with the result that the curve bends sharply upwards. If the composition of Ambalangoda moonstone were again substituted in place of Seto's analysis, Winchell's extinction-line would become straight and agree with the corresponding part of the extinction curve shown by me in fig. 4.

Further, Kôzu (16, 17) gives the optic axial angle of Ceylon moonstone 2E 120° and 125° approximately, (2V 69° and 71° approximately). As will be seen from a reference to fig. 6, these angles agree with the composition of the Ambalangoda moonstone better than with the earlier analysis given by Seto. It would therefore seem that some of Kôzu's later Ceylon moonstone samples were of the Ambalangoda variety.

Extinction on (001).—The extinction relative to the trace of (010) on flakes cleaved on (001) is straight for the great majority of the moonstones examined. Some of the specimens with white schiller showed an oblique extinction up to 2°.

Absence of Microcline Twinning.—No evidence of microcline twinning was observed in any of the numerous cleavage-flakes or ground sections of moonstone examined.

Optical Orientation and Axial Angle.—A section cut parallel to (010) shows a symmetrical interference-figure in convergent polarized light. The plane of the optic axes is perpendicular to (010), and the obtuse bisectrix, which is the direction of slow vibration, is parallel to the crystallographic axis *b*. Thus, the felspar belongs to the normal orthoclase type. The optic axial angles (2V) of the various specimens examined range between 68° and 73°.[1]

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[1] D. S. Byelyankin (5) gives the following results for a specimen of Ceylon orthoclase (var. moonstone ?): Composition approximately $Or_{61\cdot5}Ab_{36\cdot5}An_{2\cdot0}$. Specific gravity 2·582. Optic axial angle (2V) 70°. These figures correspond very closely to those of the Ambalangoda moonstone.

C. *Chemical Composition.*

Four representative specimens were selected for physical and chemical tests: A, with silky white schiller; B, pearly white schiller; C, sky-blue schiller; D, blue schiller.

	A.	B.	C.	D.
SiO_2	65·42	65·21	64·73	64·86
Al_2O_3	19·45	19·62	19·57	19·66
Fe_2O_3	0·20	0·05	trace	trace
MgO	0·12	0·15	0·10	0·10
CaO	0·55	0·50	0·55	0·60
Na_2O	4·61	4·48	4·07	3·90
K_2O	9·80	10·02	10·65	10·65
Ign. loss	0·20	0·20	0·22	0·25
	100·35	100·23	99·89	100·02
Sp. gr. at 15°C.	2.579	—	2·5775	—
Potash-felspar	58·16	59·46	63·20	63·20
Soda-felspar	38·97	37·87	34·40	32·97
Lime-magnesia-felspar	3·31	3·21	3·21	3·41
	100·44	100·54	100·81	99·58

It would seem from these analyses that the production of the schiller colour in these moonstones has been influenced by the relative proportions of soda and potash in the felspar. Many other complete and partial analyses were carried out on moonstones from the Ambalangoda mine, and in all cases the soda and potash figures were within or near the limits of the above four analyses.

Method of Determination of Alkalis.—Recent attempts by H. L. Alling (1), S. Kôzu (14–19), O. B. Bøggild (3), and others to work out relationships between chemical composition and physical properties in the alkali-felspars have shown the need for reliable determination of potash and soda in the felspars of this group. Many of the analyses in the past were made before the importance of the soda-potash ratio was realized, and it can hardly be a matter for surprise if, in some of them, the soda and potash figures should be open to question. Bøggild, discussing the collective analyses of a number of schillerized potash-soda-felspars, rightly concluded that three of them, in which the soda is shown as nil, cannot be correct, since their schiller is probably due to a fine lamellation of potash- and soda-felspar.

If the relationship between chemical composition and physical properties in these schillerized microperthitic felspars is to be fully worked out, it is essential that accurate determinations of the alkalis should accompany determinations of the physical properties for each specimen examined. A study of the equilibrium diagram of these felspars (p. 322) shows that schillerization may occur within fairly wide limits of chemical composition, and there is no justification for the assumption, often tacitly made in the past, that Ceylon moonstone has a definite chemical composition.

The determination of potash and soda in an alkali-felspar presents no great difficulty, and there is no reason why results for potash and soda should not be readily obtained correct to the nearest 0·1 % at least. In the moonstone analyses carried out in this investigation, the alkalis were determined by the Lawrence Smith method and checked by the hydrofluoric acid method, the soda being calculated in each case by difference from the weights of mixed chlorides and perchlorates. For these and similar felspars low in lime and magnesia the hydrofluoric acid method has many claims to preference. The method is rapid and accurate and it has the additional advantage that it yields checks on the alumina, lime, and iron.

Bromide Method.—It has been found (28) that a greater degree of accuracy can be obtained in the potash and soda determinations by substituting ammonium bromide and hydrobromic acid for ammonium chloride and hydrochloric acid. The resulting mixed bromides are cleaner, less fusible, and less volatile than the chlorides, and the combined weight is about twice that of the latter. The potash separation can be carried out, as usual, by the perchlorate method; or, alternatively, by adding platinic bromide, the mixed platinobromides can be produced and the relatively insoluble potassium salt separated in the usual manner.

4. PARTLY-DECOMPOSED MOONSTONE (DE-ALBITIZED PERTHITE).

A. *Megascopic Characters.*

Reference has been made on p. 295 to the fragments of partly decomposed moonstone occasionally found amongst the felspar residues of the Ambalangoda mine. They occur as tablets or rectangular rhombs bounded by the basal plane (001), the pinakoid (010), and the schiller or decomposition plane Δ. The fragments show no disposition to cleave along the usual directions (001) and (010). Instead, a very prominent, almost micaceous, parting along the schiller or decomposition plane has been developed.

In some specimens decomposition (or de-albitization) is not complete; small hard patches here and there possess the original blue or white schiller and show the two principal cleavages on (001) and (010), the parting on the decomposition plane not being prominent in these patches. One specimen exhibited decomposition in one half, with the remainder quite clear and fresh and showing a bluish-white schiller. In the fresh portion, the cleavages parallel to (001) and (010) are well developed; in the decomposed portion these cleavages have become subsidiary to the parting parallel to the decomposition plane Δ. The identity of this plane of decomposition and the schiller plane is shown by rotating this specimen about an axis in the plane Δ, when the blue schiller of the fresh portion and the pearly lustre of the decomposed portion reflect simultaneously.

Measurement of Angle Δ : (001).—The ease with which these decomposed stones can be split along the plane of decomposition Δ and the fact that the original basal plane (001) is present permit a fairly accurate goniometric measurement of the angle between the parting or schiller plane Δ and the basal plane to be made. Eight samples of this de-albitized perthite were selected, and after each specimen had been cleaved to obtain a clean smooth surface along the plane Δ small cover-glasses were cemented on this face and on the (001) face to obtain good reflecting surfaces. The many goniometric measurements showed in the means for each sample a range from 73° 23′ to 74° 27′ for the angle Δ : (001), the mean value for the whole series being 73° 53′. This gives for the plane Δ the indices (13.0.$\bar{2}$), for which the calculated value is 74° 3′ (from $a : b : c = 0{\cdot}6585 : 1 : 5554$, $\beta = 63° 57′$).

Measurements by previous workers of the angle Δ : (001) have usually depended on internal reflection from the schiller plane. F. E. Reusch (25) obtained by this method for moonstone (Ceylon), 73° 54′; soda-orthoclase (Fredriksvärn), 74°; adularia (Zillerthal), 74° 18′. Whitman Cross (11), by a similar method, obtained the angle 72° 53′ for a schillerized sanidine from the Chalk Mountain, Colorado. He concluded that the corresponding orthodome was (15.0.$\bar{2}$). Brøgger (4) determined the angle for schillerized Norwegian felspar (cryptoperthitic) to be 72° 2′, and concluded that the orthodome was $(80\bar{1})$. Recently Bøggild (3, pp. 19–21) has measured this angle for a number of schillerized alkali-felspars. He obtained angles varying between 72° 18′ and 75° 32′, and concluded that the schiller plane cannot correspond to any fixed crystallographic plane. For Ceylon moonstone he found the angle to be 73° 5′.

The discrepancy between these values may be due to the error attendant upon measuring the angle by the internal reflection method, or it may be that the inclination of the perthite or schiller plane to the plane (001) varies slightly with the composition of the felspar.

B. *Microscopic Characters.*

Under the microscope these de-albitized specimens exhibit all the transition stages of de-albitization from (*a*) practically fresh blue moonstone to (*b*) completely leached or de-albitized microperthite.

(a) *Fresh variety.* The hard, clear, and undecomposed portions of these stones cleaved on (010) show a structure resembling that of an ordinary blue stone, except that the field of view is divided at fairly regular intervals by narrow lamellae of coarse albite, similar to the large so-called primary albite common in most perthitic felspars. These lamellae are about 0·2 to 1 mm. in length and about 0·005 mm. in thickness. They lie in the plane of schiller and grade down as isolated individuals into the ordinary (or, ab) microperthite previously described. The felspar between the large albite lamellae possesses the same micro-structure as that of the ordinary blue or blue-white moonstone. The mean extinction, on (010), of this microperthitic groundmass varies between 9·8° and 10·5° for different specimens examined, that of the large albite lamellae being about 18°.

Plate XIII, fig. 5, shows the large albite lamellae in a cleavage-flake taken from the clear fresh portion of one of these specimens. The cleavage-flake is shown under crossed nicols with the microperthitic groundmass near the extinction position in order to throw into prominence the large albite lamellae. The (or, ab) microperthite is too fine to be seen in this photograph, but the (Or, Ab) ‘ shadow ’ perthite shows faintly in places.

(b) *Decomposed variety.*—In the first stage of decomposition these specimens become opaque and lose their perfect cleavage on (001) and (010), and an incipient parting on the plane Δ is developed. This is seen in thin sections to be caused by the gradual destruction of the large albite lamellae and the formation of large flat cavity plates or lenses parallel to the schiller plane and partly filled with kaolin. As decomposition proceeds still further, the walls of the cavities are attacked and the fine albite of the (or, ab) microperthite is destroyed. The large cavities broaden and adjacent ones tend to coalesce. The fine microperthitic albite in the intervening groundmass is attacked more and more until de-albitization is complete. A very delicate skeletal meshwork of interlacing laminae of orthoclase and kaolin is the final result.

Sections on (010).—Plate XIII, fig. 6, shows the appearance of one of these decomposed stones in a section ground parallel to (010), magnified 200 diameters. The section has been stained with methylene blue to show up the kaolin, which thus appears black in the picture. The large lenses of kaolin have a length of about 0·5 to 2 mm. and a thickness of 0·005 to 0·015 mm. They lie mainly along the trace of the schiller plane Δ with a tendency to anastomose into the trace of (100). The intervening areas or zones consist of fine alternating lamellae of orthoclase and kaolin, the orthoclase being the (or) residue from the destruction of the (or, ab) microperthite, the kaolin partly filling the cavities originally occupied by the albite lamellae.

In view of the extreme thinness of these orthoclase laminae, their freshness and freedom from kaolinization is remarkable. Even when so fine as to be almost invisible, and interleaved between kaolin lamellae, the orthoclase is clear and gives a sharp extinction under crossed nicols. The average length of the individual orthoclase lamellae is about 0·005 to 0·01 mm. and their thickness about 0·0008 mm. or less. They lie mainly along the trace of Δ.

Extinction on (010).—All the felspar lamellae in the section on (010) extinguish uniformly at an angle of 5·4° relative to the trace of (001). This extinction corresponds to that of normal or low-soda orthoclase. Hence the conclusion is reached that the residual mineral is orthoclase, a conclusion confirmed by the analyses shown on p. 313.

(Ab) Structure on (010).—In the stained section (pl. XIII, fig. 6), a number of partly dyed, darkish bands can be seen to cross the bright zones of orthoclase felspar at an angle of about 10°. They appear as vertical bands in the photograph. These bands vary in width from 0·005 mm. to 0·01 mm. They lie mainly along the trace of

(100), with frequent branchings into the trace of Δ. The fine orthoclase and kaolin lamellae of the (or, ab) structure maintain their direction (parallel to the trace of Δ) as they pass from the bright areas into the darker, partly dyed, oblique bands, but the orthoclase lamellae become thinner and the kaolin lamellae thicker in the dark areas. These darker areas, richer in kaolin, undoubtedly represent the original coarse (Ab) lamellae of the (Or, Ab) perthite, and the bright areas correspond to the (Or) lamellae.

Section on (001).—A section of one of these fully de-albitized specimens cut parallel to (001) is shown in pl. XIV, fig. 7, magnified 200 diameters. The section has been stained to show up the kaolin. The large kaolin lenses have about the same length and breadth as in (010) sections, their direction being parallel to the trace of Δ. The intervening areas of fine orthoclase-kaolin lamellae are very much cut up and interrupted in this picture by numerous dark bands corresponding to decomposed (Ab) areas which cross the bright (Or) zones along prism directions at about 23° on each side of the trace of Δ. These dark bands are narrower, shorter, and appear to be more numerous than in (010) sections. They show a disposition to run off into the trace of Δ and into another prism direction at an angle of about 33° to the trace of Δ. The first prism direction corresponds to (320) and the second to (110).

The fine microperthitic orthoclase-kaolin lamellae are much shorter than in (010) sections. They lie parallel to the trace of Δ and, as in (010) sections, the direction is maintained when the lamellae pass from the bright areas into and across the obliquely-lying dark bands, and the same thickening of the kaolin and thinning of the orthoclase in the dark bands occurs.

Optic Axial Angle.—Plates of de-albitized felspar, up to one or two millimetres in thickness, can be rendered almost transparent by boiling for some time in Canada balsam. Specimens treated in this way show a faint schiller. The optic axial angle (2V) measured on these specimens is about 56°.

C. *Chemical Composition.*

The analyses of three samples of this de-albitized moonstone are given below, the first representing partly de-albitized material with some undecomposed perthite, the second containing a little free albite, and the third being a completely de-albitized moonstone.

	1. Partly de-albitized.	2. De-albitized.	3. Thoroughly de-albitized.
SiO_2	61·80	62·30	62·30
Al_2O_3	21·40	21·80	21·74
Fe_2O_3	—	trace	trace
MgO	0·15	—	0·10
CaO	0·42	0·64	0·50
Na_2O	2·36	1·12	0·88
K_2O	12·15	12·58	12·82
Ign. loss	0·98	1·85	2·02
	99·26	100·29	100·36
Potash-felspar	74·36	74·55	76·25
Soda-felspar	19·92	9·46	7·43
Lime-felspar	2·08	3·16	2·48
Kaolin	2·96	13·02	14·20

These analyses confirm the conclusions arrived at from an examination of microscope sections. The decomposition has proceeded by way of partial leaching and partial kaolinization of the albite constituent of the moonstone.

Residual Soda-felspar.—Although a microscopic examination of the decomposed stones shows that all the albite lamellae have been removed or destroyed, the above analyses prove that there is still about 7·5 % of soda-felspar in the residue. This soda-felspar is probably present in the form of a solid solution in the orthoclase lamellae, and this amount may be taken as the approximate quantity capable of being retained in solid solution in orthoclase under normal conditions of equilibrium. Calculated on the total residual felspar present, the amount is about 9 %, a figure very close to that deduced by C. H. Warren (30, pp. 142–143) for a number of perthitic felspars examined by him.

Proportion of Felspar destroyed by De-albitization.—Determinations of the porosity of several decomposed stones gave about 33 % pore-space. The amount of kaolin present is 14 %, so that the total volume of felspar destroyed is about 47 %. If this were all soda-felspar, the original undecomposed moonstone would have contained about 51 % of this component, a quantity slightly in excess of that in a white moonstone. The actual quantity of soda-felspar removed, however, must have been less than 40%, for two reasons: (1) the albite lamellae of the (or, ab) microperthite must have held in solid solution some potash-felspar which would be destroyed along with the albite; (2) there has been some decomposition of the orthoclase lamellae, particularly in the neighbourhood of the large albite lamellae.

For the potash held in solid solution in albite under equilibrium conditions, Warren gives the figure of 8 % (= about 3 % on a total of 40 %). Of the amount of the free orthoclase lamellae destroyed, it is not possible to make a reliable estimate, but judging from the relative size of the original large albite lamellae and the corresponding large decomposition lenses, I should estimate that the figure is probably about 15 % (or about 9 % on a total of 60 %). With these corrections, the proportion of soda-felspar in the original undecomposed felspar would be about 35 %, which is about the same amount as that in blue moonstone.

Agents of De-albitization.—We see in these remarkable specimens[1] a perfect example of selective decomposition carried out by natural agents. The complete removal of the albite lamellae, leaving the orthoclase practically unscathed, has laid bare to the microscope in a striking manner the peculiar heterogeneous structure of these Ceylon moonstones. The search for similar structures in fresh undecomposed specimens and the confirmation of their presence by various experimental methods have mainly followed, as a matter of course, from the first careful examination of these de-albitized specimens.

The perfect selectivity of the decomposition leads one to inquire in what special manner the leaching or de-albitization has been brought about. It has been suggested on p. 295 that the presence of organic matter at considerable depth in the kaolinized pegmatite of this area indicates that meteoric waters have played a part in the decomposition. Meteoric action, however, usually brings about kaolinization of the potash-felspar as well as the soda-felspar, whereas in the above decomposition the soda-felspar has been, in the main, leached away.

It may be that magmatic gases, acting penecontemporaneously with the pegmatite intrusion (pneumatolysis), have been in part responsible for the kaolinization of the pegmatite and the selective decomposition of the perthite. The association of graphite with this pegmatite and the common occurrence of this mineral in veins and granulites to the south of this area have been already mentioned. Also, A. K. Coomaraswamy (7) and T. H. Clark (6) have independently suggested that magmatic gases have, in some cases, played the

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[1] Representative specimens of this de-albitized moonstone may be seen in the Mineralogical Department of the British Museum and the Geological Department of the University of Liverpool.

rôle of carrier and concentrator for the carbon of these deposits. This view is strengthened by the association of scapolite, sphene, calcite, &c., with the graphite.[1]

A relevant note on an interesting specimen from the Ambalangoda mine may here be inserted. As collected it was a sample of marcasite, about the size of an egg, with pieces of blue moonstone embedded in it. As a result of storage for four to six years in a damp Lancashire climate, the marcasite has been reduced to a powdery condition, leaving free the moonstone, which consists of very irregular fragments with blue schiller, together with a few pieces of white, partly de-albitized stone. The specimen evidently represents a deposit of marcasite in and around the partly-decomposed felspars of the pegmatite. The curious fact, however, is that no kaolin is enclosed in the marcasite. This suggests that the kaolin now present in the mine may have been formed since the de-albitization phase of decomposition took place, i.e. mainly from the potash-bearing lamellae left after de-albitization.

Whatever were the special conditions which brought about this form of decomposition, the solvent action has been very highly selective on the albitic member of the (or, ab) microperthite. If the same kind of selective decomposition could be brought about in the laboratory, the method would be of considerable value in providing much-needed data to help towards the elucidation of the alkali-felspar equilibrium diagram, just as selective decomposition of mixed alloys has been used in the elucidation of alloy equilibrium diagrams.

After many unsuccessful attempts to bring about selective decomposition of these perthitic moonstones, using various reagents in different concentrations at ordinary laboratory temperatures, I have obtained a partially selective decomposition by heating the felspar under very high pressure in a steel bomb, with water (steam) and carbon dioxide. The results of these tests are described on pp. 357–361.

5. EFFECTS OF HIGH TEMPERATURES ON THE SCHILLER AND MICRO-STRUCTURE OF AMBALANGODA MOONSTONE.

In his X-ray examination of moonstone from Ceylon and Korea S. Kôzu (14) observed that while the mineral appeared to show no

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[1] I have since found schillerized felspars in the pegmatites of the Khondalite Series, Kanchupara, with which graphite is associated.

evidence of heterogeneity under the microscope, X-ray analysis showed a double Laue spot system which could be gradually resolved into a single system by heating the moonstone to a temperature between 700° and 1100° C. At the same time the schiller was found to become less intense, and at a temperature approaching 1100° C. it almost disappeared. From these results Kôzu concluded that the schiller was caused by a double arrangement of the net-planes of the space-lattice.

In a similar manner, the schiller of the Ambalangoda moonstones can be diminished or completely destroyed by heat-treatment. A microscopic examination of the treated specimens shows that the change in schiller is accompanied by a modification of the microperthitic structure.

The following tabulated results of heat-treatment on various fragments of the two specimens A and C, the analyses of which are given on p. 307, indicate the nature of the changes which can be brought about by heating Ambalangoda moonstones. These tests were carried out in a platinum resistance furnace with a platinum-rhodium thermocouple attached to a chart recorder. The thermocouple was calibrated at the beginning and at the end of each test.

Specimens heated to 850°C. for 4 hours and cooled in air.

	A (white).	C (blue).
Effect on schiller.	Schiller intensity reduced. Bluish tinge develops.	Becomes very faint with a violet tinge.
Effect on (or, ab) microperthite.	(or, ab) microperthitic boundaries become indistinct in ordinary light, under crossed nicols still clearly visible.	Intensity of (or, ab) microperthite structure under crossed nicols reduced.
Effect on (Or, Ab) structure.	(Or, Ab) structure appears to be unaltered by the treatment.	(Or, Ab) structure appears to become more pronounced, especially on (001) flakes.
Effect on extinction on (010) relative to trace of (001).	Average extinction reduced from 10·5° to 9·5°.	Average extinction reduced from 10·0° to 9·0°.
Effect on specific gravity.	Reduced from 2·579 to 2·5670.	Reduced from 2·5775 to 2·5670.

Specimens heated to 980°C. for 6 hours and cooled in air.

	A (white).	C (blue).
Effect on schiller.	Schiller very faint, with bluish-white tinge.	Schiller becomes very faint, with violet tinge.
Effect on (or, ab) microperthite.	(or, ab) structure nearly invisible in ordinary light, but still readily visible under crossed nicols.	Structure practically destroyed even when viewed under crossed nicols.
Effect on (Or, Ab) structure.	(Or, Ab) structure appears to be unaltered.	(Or, Ab) structure appears to be more pronounced than in unheated specimen.
Effect on extinction on (010).	Reduced from 11·0° to 8·5°.	Reduced from 10·0° to 8·5°.
Effect on specific gravity.	Reduced from 2·579 to 2·5670.	Reduced from 2·5775 to 2·5670.

Specimens heated to 1050°C. for 12 hours and cooled in the electric furnace.

	A (white).	C (blue).
Effect on schiller.	Very faint bluish-white schiller not strictly confined to original schiller plane.	Specimen becomes glass clear, no schiller.
Effect on (or, ab) microperthite.	(or, ab) perthite boundaries disappear completely in ordinary light. Structure still visible under crossed nicols, but less sharply defined.	No visible evidence of (or, ab) microperthitic structure even under crossed nicols and optimum conditions of illumination.
Effect on (Or, Ab) structure.	(Or, Ab) shadow perthite structure becoming relatively more prominent than (or, ab) microperthitic structure.	(Or, Ab) shadow perthite structure still undiminished in intensity.
Effect on extinction on (010).	Reduced from 11·0° to 8·0°.	Reduced from 10·0° to 7·5°.
Effect on specific gravity.	Reduced from 2·579 to 2·566.	Reduced from 2·5775 to 2·566.

Plate XIV, fig. 8, illustrates the effect of heat-treatment (12 hours at 1050° C. as in the above test) on sample A, the white stone of previous tests. The photograph shows a cleavage flake on (010) magnified 185 diameters and seen under crossed nicols. The fine (or, ab) structure of pl. XIII, fig. 2 (same specimen untreated) has now lost its sharp distinctness, but the (Or, Ab) structure is still prominent. Pl. XIV, fig. 9, shows a cleavage flake on (001) of the same specimen seen under crossed nicols. The (Or, Ab) structure appears to be sharper even than in the untreated moonstone.

Specimens heated to 1120°–1130°C. for 12 hours and cooled in the electric furnace.

	A (white).	C (blue).
Effect on schiller.	Sample opaque due to partial fusion; shape partly retained but cleavages gone.	Specimen glass clear.
Effect on (or, ab) microperthite.	Microperthitic structure destroyed. Crystallites visible in a glassy matrix.	(or, ab) structure completely destroyed even under crossed nicols.
Effect on (Or, Ab) structure.	(Or, Ab) structure destroyed.	(Or, Ab) structure fairly prominent under crossed nicols.
Effect on extinction on (010) relative to trace of (001).	Structure destroyed. No measurable extinction.	Reduced from 10·0° to 7·0°.
Effect on specific gravity.	Below 2·565.	Reduced from 2·5775 to 2·565.

The results prove that:

(*a*) The schiller and microperthitic structure of these moonstones can be destroyed by heat-treatment. The changes commence at about 500°–700° C., and in the case of most of the blue moonstones examined the destruction of the schiller and of the visible (or, ab) microperthitic structure is complete on heating to about 1050° C. for 6 to 12 hours. In most of the white and many of the blue-white specimens the (or, ab) boundaries as seen in ordinary light are destroyed between 700° and 900° C., but a faint elusive schiller still persists, and this schiller, together with the (or, ab) structure, as seen under crossed nicols, does not completely disappear until near the fusion-point of the felspar.

The intensity of the schiller varies progressively with heat-treatment, and the colour also changes with the intensity, the tendency being from white, through blue, to faint blue-violet, and finally colourless. As the intensity diminishes, the schiller appears to be less sharply confined to a definite plane. Time appears to be a factor in the diminution of the schiller and microperthitic structure by heat-treatment.

(*b*) The coarser (Or, Ab) shadow perthite, or prism structure, appears to become more prominent with heat-treatment up to a temperature of about 1050° C., and certainly does not diminish in intensity up to 1000° C. It begins to disappear rapidly at temperatures near incipient fusion of the felspar. The increase in intensity up to 1000° C. is more noticeable in the blue stones, especially on (001) sections, probably because the fine (or, ab) structure is very faint in these specimens and on these sections.

(*c*) The rate of cooling of the heated specimens has little or no effect on the schiller and (or, ab) microstructure. The visible changes brought about by heat-treatment are not reversed to any measurable extent by cooling quickly or cooling slowly, within the time-limits of these laboratory experiments.

(*d*) The extinction-angle on (010), and the specific gravity of these moonstones are both reduced by heat-treatment. The reductions appear to be caused in the first place by the partial merging of the (or, ab) components in each other. It has been shown in previous pages that the extinction-angles of the untreated specimens are very near the calculated means of the orthoclase and albite components, and the reduction can be explained by a partial re-solution of the lamellae in each other on heating. This view is strongly supported by the behaviour of the alkali-felspars from other localities described in the later pages of this paper.

The Cause of the Schiller.

W. C. Brøgger (4) appears to have been the first to associate schiller in alkali-felspars with microperthitic structure. In his description of the felspars of the Norwegian syenites he suggested that the schiller of these felspars was due to the scattering of light from the microperthite or cryptoperthite lamellae.

It has already been mentioned that S. Kôzu (14), in an examination of moonstones from Ceylon and Korea, found no visible signs of heterogeneity, such as lamellar structure or inclusions.[1] An X-ray analysis showed, however, that these moonstones differed from the non-schillerized adularia of St. Gotthard in the form of the Laue spot diagram. Adularia shows a single-spot diagram, while the diagram for Ceylon and Korea moonstones is double. On being heated, the Korea specimen loses its schiller completely at 700 ° C. and the Laue spot diagram becomes a single one. For the Ceylon moonstone (of Kôzu) a much higher temperature is required, the double Laue spot system only approaching to a single one at a temperature of about 1100° C., that is, near the fusion-point of the felspar. On being cooled, the Ceylon moonstone shows a reverse change, the single-spot system becoming double. The spots widen out as the temperature is reduced until the temperature of 700° C. is reached. The Korean moonstone, which shows a single-spot system on heating to 700° C., retains a single spot on cooling.

From these results Kôzu and Endô conclude that the schiller of these moonstones is due to a double arrangement of the net-planes of the space-lattice and that mixed soda-potash-felspars of the Korean and Ceylon types suffer an irreversible change on being heated to a temperature of 500–700° C., whilst above the latter temperature, up to near the fusion-point of the felspar, any further transformation of the felspar towards a single space-lattice structure is of a reversible kind.[2]

It would be interesting to know whether, in Kôzu's experiments, the schiller colour of the Ceylon moonstone reappears with the return of the double Laue spot system on cooling. If the schiller is due, as Kôzu and Endô suggest, to the double arrangement of the net-planes of the space-lattice, one would expect that a return to a double Laue spot system, and the concomitant return to a double arrangement of the net-planes, would be accompanied by a reappearance of schiller colour. None of the Ceylon specimens that I heat-treated gave any

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[1] In a later paper Kôzu (19) refers to two different kinds of Ceylon moonstone, one with whitish pearly lustre and translucent by transmitted light, and the other with a schiller like that of kerosene fluorescence. It is not stated which type was used in the analysis or microscopic examinations, but it is almost certain that the pearly type would show a good microperthitic structure on (010) under crossed nicols.

[2] Investigations by Kôzu and Saiki (18) have shown that the relatively rapid changes in the expansion at temperatures of 500–700°C. and 900°C. are not reversible changes by the method employed.

indications of a reappearance of schiller on cooling, even when the cooling time was extended over several hours. Neither was there any noticeable reappearance of the destroyed, or partly-destroyed, (or, ab) microperthitic structure. The change is an irreversible [1] one within the cooling time employed. Further, the persistence of the (Or, Ab) 'shadow' structure in the blue stones after the complete destruction of the schiller, and the presence of both sets of structures in white stones from which the schiller has been almost removed by heating, show that a regular heterogeneity, even of visible microscopic dimensions, can exist in this Ceylon moonstone without causing schiller.

We have seen on p. 297 that the (or, ab) microperthite is coarsest in the white moonstone and that it decreases in size and visibility through the blue-white to blue stones. In fact, with a little practice one can predict, with a fair degree of accuracy, the colour and intensity of schiller of these moonstones from a microscopic examination of the microperthitic structure of cleavage-flakes on (010), especially with white and blue-white varieties. Moreover, it will be shown later that the Ragged Mountain 'sanidine', which possesses alternating schiller zones from white to pale blue, exhibits corresponding differences in microperthitic structure. In sections parallel to (010) the white zones are seen as fairly coarse, sharp microperthite, which changes abruptly into fine, almost invisible, microperthite as one passes across the border into a blue zone.

From these various observations I conclude that the schiller is due to microperthitic or submicroperthitic (cryptoperthitic) structure, as first suggested by Brøgger. The schiller appears to depend mainly on the scattering of light from the boundaries between the (or, ab) microperthite lamellae. If the boundaries are numerous, sharp, clear, and regular, the schiller is white; if the boundaries are fairly regular, but not so sharp and clear, the light becomes scattered within a limited range, and the schiller colour is blue, the schiller plane still being fairly sharply defined. When the (or, ab) boundaries have completely merged, the schiller is practically destroyed, although evidence of the presence of (or, ab) microperthite may still persist, as seen under the microscope and demonstrated by the etching tests referred to on pp. 358-361.

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[1] The term 'irreversible', as used in this paper, only applies of course to laboratory times. It is evident that for the original cooling times of the felspars, during and after their formation, these changes must be regarded as reversible.

6. SODA-POTASH-FELSPAR EQUILIBRIUM DIAGRAMS.

A. *Vogt and Warren's Diagram.*

From the time that J. H. L. Vogt (29) in 1905 first suggested that the soda-potash-felspars form a 'broken series' of mixed crystals according to type V of Roozeboom's classification, the question of the true relationship between these two felspars has been the subject of repeated investigation and controversy.

The problem has been approached along different and distinct lines by different workers. The method first adopted by Vogt, and later by E. Mäkinen (20), was to collect analyses of plutonic and hypabyssal rocks bearing soda and potash. These investigators then deduced, by convergence from the non-perthitic to the highly perthitic felspar types, the limit of the immiscibility gap and the eutectic point. The uncertainty of some of the older analyses and the manner of interpreting the results were weaknesses of this method. Mäkinen, using the same method (and to a large extent the same analytical and petrological data) as Vogt, arrived at very different conclusions from the latter regarding the position and extent of the immiscibility gap. Vogt's diagram, with Warren's (30, p. 148) later modification of the lower points in the solidus area, is reproduced in fig. 2.

Vogt (29, pp. 539–541) suggested that many of the perthitic separations appeared to have taken place from the solid state (indeed he pointed out the analogy between these separations and the separation of carbon from steel) and he drew the lines *AL* and *BM* inclined to the vertical to indicate an increase in the immiscibility gap for the solid phases on cooling. He made no attempt, however, to determine the positions of the two points *L* and *M*. He further pointed out that this separation of microperthite appears to be associated in many cases with the change of orthoclase into microcline.

C. H. Warren (30) endeavoured, from a chemical and microscopic examination of ten selected perthitic felspars, to fix the lower points *L* and *M* of Vogt's equilibrium diagram by determining the amount of soda-felspar in the orthoclase member of the perthite, and vice versa. It was, of course, assumed by him that these perthites had reached equilibrium conditions. Warren found about 8 % of felspar in solid solution in each case, and these figures have since been adopted by most workers. Warren agreed with Vogt's suggestions that many of the perthites were separations from solid solutions, and that the inversion of orthoclase to microcline appeared to favour this separation. He indicated this reduced 'solubility' on inversion by the horizontal line Pyy_1 on the diagram. According to this line, an orthoclase of composition P would, on inversion to microcline at temperature T_2, only be able to hold about 8 % of albite in solid solution, the remaining 12 % separating as perthite at that temperature.

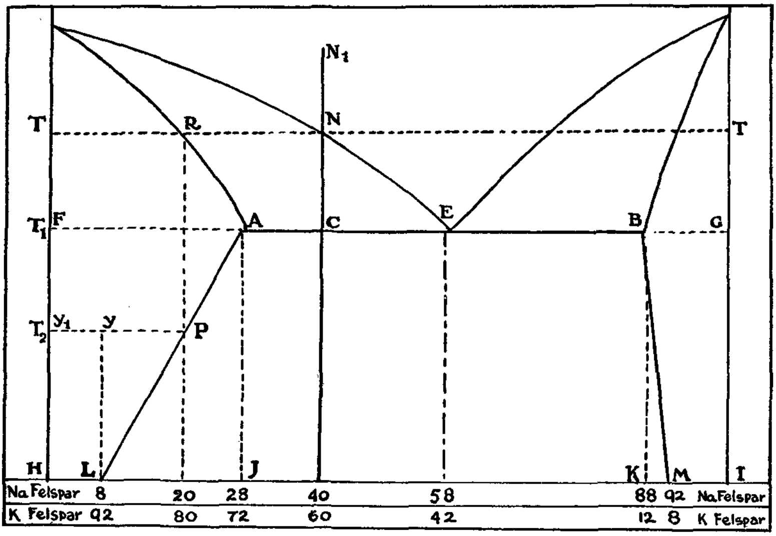

FIG. 2. Potash-soda-felspar equilibrium diagram. (After Vogt and Warren.)

Let us consider for a moment the results of cooling a potash-soda-felspar magma of composition 40 % soda-felspar and 60 % potash-felspar, assuming that it solidifies according to the diagram (fig. 2). On reaching the solidus-liquidus line at N (temperature T), crystals of composition R would begin to separate. This would leave the magma richer in the soda component, and as cooling proceeded the composition of the magma would travel along the curve NE. At the same time the composition of the crystals separating from the magma would travel along the curve RA.

When the temperature had fallen to T_1 and the composition of the magma had reached the eutectic or lowest melting-point E, the magma would crystallize as a eutectic mixture of two phases having the composition A and B respectively. The temperature would remain at T_1, until solidification was complete. This assumes no undercooling or metastable conditions.

The resulting felspar-rock would thus consist of: (1) a series of more or less idiomorphic felspar crystals ranging in composition from *R* to *A* (and possibly zoned with an increasing soda-felspar content towards the outside); and (2) allotriomorphic felspar intergrowths of composition *A* and *B*.

Vogt fixed the immiscibility gap in the above diagram at 72 % and 12 % for the potash-felspar, and the eutectic at 42 %. E. Mäkinen (20, p. 49) concluded that these figures were extreme. He found the eutectic point to be at 30 % of potash-felspar and drew a very short immiscibility gap extending about 3 to 4 % on each side of the eutectic point. E. Dittler (12) endeavoured to determine the form of the solidus-liquidus curves by direct fusion of felspar mixtures. From his results he concluded that there was no immiscibility gap, and that separation took place according to type III of Roozeboom.

H. L. Alling in a recent summary account of felspars has embodied these interpretations in a three-dimensional form (1, vol. 31, p. 289, fig. 2 C) which makes each of the above diagrams possible for certain conditions of cooling. Thus he suggests that Vogt's diagram may represent the conditions obtaining with pegmatites; whereas with plutonic types of cooling, the diagram of Mäkinen may more nearly represent the conditions of crystallization.

It should be remembered that the evidence put forward by Vogt and others for this binary diagram of the alkali-felspars has in the main been derived from studies of rocks containing more components than these two felspars. Most, if not all, of these alkali-felspar rocks, low in lime and ferromagnesian minerals, contain free quartz as a third component, and in many cases the magma probably contained liquid and gaseous mineralizers in addition. Hence the true equilibrium diagram for these conditions should be of ternary or quaternary rather than of binary type. The fact that the binary diagram can be applied with a fair degree of approximation to the behaviour of the two felspars when crystallizing from such rock-magmas shows that the additional components have not seriously affected the behaviour of the felspars during crystallization. This may be due to the relative insolubility of these components in the felspar phases.

The main effect of these additional components appears to have been to provide a lower melting-point ternary or quaternary eutectic, from which the two felspars (and in some cases quartz) could continue to separate as phenocrysts even after the binary eutectic of the two-component felspar-diagram (corresponding to the *immiscibility gap A–B*) had been reached. This assumes that the two felspars were present in excess of the ternary or quaternary eutectic, as they appear to have been in some of the magmas referred to in this paper.

Morey and Bowen (23) have shown, by direct fusion experiments, that orthoclase decomposes into leucite and silica on melting, so that quartz in excess, as a third component, appears to be an essential to the separation of potash-felspar, although the usually accepted binary diagram for these felspars ignores its presence.

B. *Application of Eutectic Diagram to Ambalangoda Moonstones and Pegmatites.*

It was pointed out on p. 307 that all the moonstones analysed from the Ambalangoda mine came within fairly narrow limits of composition, that is, between 30 % and 40 % of soda-felspar and 60 % and 70 % of potash-felspar. It has been explained that this potash-soda-felspar probably represents the residue from a very special form of decomposition of a pegmatite from which the albite member has been removed, partly by being dissolved out and partly by kaolinization.

The natural inference would be that this residual felspar represents the potash-felspar side of a mixed crystal separation on the lines of the diagram of Vogt and Warren, the soda-potash-felspar or albitic side of immiscibility gap having been removed by decomposition.

A pegmatite (at X on map, fig. 1) about 400 yards to the north of the moonstone mine, and evidently, from its mineral assemblage, the same pegmatite as the original of the mine, was found to have the following composition:

SiO_2.	Al_2O_3.	Fe_2O_3.	FeO.	MgO.	CaO.	Na_2O.	K_2O.	Ign.	Total.
74·65	14·45	0·70	trace	0·20	0·66	3·68	5·70	0·21	100·25

The ratio of sodium oxide to potassium oxide in this rock is higher than in the moonstone. If converted into felspar and the total brought to 100, the proportions are: potash-felspar 51·6, soda-felspar 48·4 %. This ratio, although higher in soda-felspar than the moonstones, is still on the potash-felspar side of Vogt's eutectic composition, and the first felspar to separate from a magma of the above composition would be one lower in potash than the magma itself.

Let us consider the result of cooling such a magma, assuming that the felspars crystallize according to the binary diagram of Vogt and

Warren, except that the point *A* of the immiscibility gap is altered from 28 % of soda-felspar to 40 % to correspond with the composition of the Ambalangoda white moonstone. The modified diagram is shown in fig. 3.

The line P–P_0 (fig. 3) corresponds to the composition of the Ambalangoda pegmatite. If the magma were cooled to a temperature *T*, potash-soda-felspar crystals of the composition potash-felspar 70 %, soda-felspar 30 %, would begin to separate. As the temperature fell towards T_1, the crystals separating from the magma would become richer in soda up to a maximum of 40 % corresponding to point *A*. At the temperature T_1, the remaining magma would have the binary eutectic composition *E* and further crystallization would be into *two* felspars of composition:

(*A*) Soda-orthoclase[1] . .	Potash-felspar	60 %
	Soda-felspar	40
(*B*) Albite	Potash-felspar	12
	Soda-felspar	88

The proportion of (*B*) phase in the rock would not be large, for it is only about 25 % of the total felspar present.

Further cooling of the rock below the temperature T_1 would result in exsolution of the albitic component from the potash-soda-felspar as the temperature vertical corresponding to the particular composition crossed the solid solubility line *AL*. The amount of exsolution and the coarseness of the microperthitic structure would be greatest in the felspar with 40 % of soda-component (composition *A*). It would be least, and the microperthitic structure would be finest, in the earliest separated felspar with about 30 % of soda-component.

The subsequent decomposition of such a pegmatite-rock by agents having a very selective action on the albite lamellae would yield a residue similar to that found in the Ambalangoda mine. The felspar most resistant to decomposition would be that first formed from the magma, and containing closely 30 % of soda-component. Its resistance to decomposition would be greatest because the soda-felspar would be in least quantity and in the finest state of subdivision. Thus, the residue would tend to consist mainly of felspar with blue to blue-white schiller, together with kaolin and partially decomposed felspar of the de-albitized moonstone variety.

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[1] According to Winchell's nomenclature (31), the first separations would be into (*A*) sanidine, (*B*) barbierite.

C. *Ambalangoda Microcline-pegmatite.*

Although no indications of microcline structure were found in any of the moonstones examined, or in the associated moonstone pegmatite-rock, an outcrop of pegmatite about a mile north-east of the moonstone mine (point Y on map, fig. 1) proved on examination to consist mainly of coarsely crystalline microcline-microperthite (pl. XIV, fig. 10).

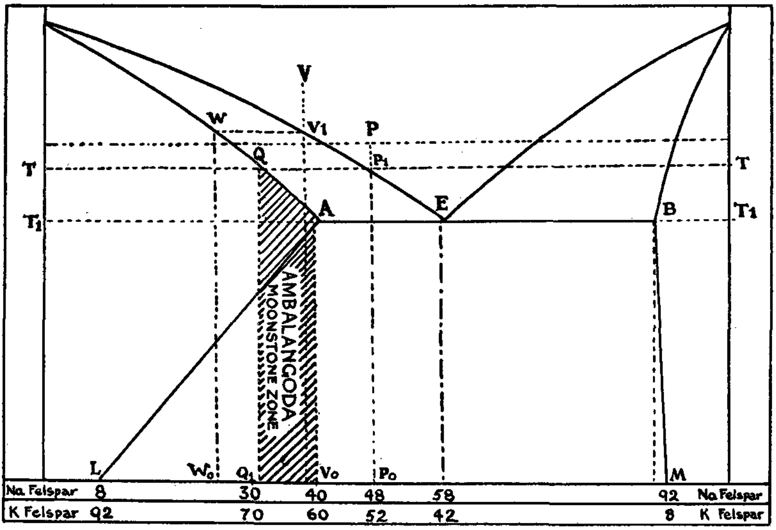

FIG. 3. Modification of Vogt's and Warren's equilibrium diagram for the potash-soda-felspars.

A portion of a large crystal of microcline was obtained from this pegmatite. The composition of the microcline and of the rock are shown below :

	Microcline-pegmatite rock.	Microcline crystal.
SiO_2	71·50	64·62
Al_2O_3	14·90	19·02
Fe_2O_3	1·12	0·40
FeO	trace	—
MgO	0·45	0·08
CaO	1·92	0·61
Na_2O	2·88	2·38
K_2O	6·80	12·74
Ign. loss	0·35	0·50
	99·92	100·35

The potash-soda ratio in this rock is higher than that in the pegmatite nearer the mine, and the lime is also higher. Except for these differences, the general composition is similar. Both pegmatites contain the same type of orthorhombic pyroxene in small quantity, also occasional flakes of graphite. The bulk of the rock consists, in each case, of felspar and quartz. The calculated amounts of felspar in the pegmatite and in the crystal are:

	Rock.	Crystal.
Potash-felspar	40·5 %	76·5 %
Soda-felspar	25·2	20·4
Lime-felspar	8·6	3·1

Although the quantity of lime-felspar in this pegmatite is greater than in the moonstone-pegmatite, Vogt (29, p. 523) has shown that greater amounts than this do not seriously affect the form of the potash-soda equilibrium diagram. Hence we may take fig. 3 as being applicable to this pegmatite-rock. Converting the alkali-felspars to 100 % we have potash-felspar 62 %, soda-felspar 38 %. This composition corresponds to the vertical line VV_0 (fig. 3) and from such a magma the first felspar crystals to separate would have the composition WW_0, or approximately 78 % of potash-felspar and 22 % of soda-felspar. This composition is very close to that of the actual fragment of the large crystal taken from the microcline-pegmatite. The proportion of (B) or soda-felspar phase separating from this magma would not be large (only about 10 %), and this would contain the greater part of the lime-felspar as plagioclase.

Attempts to isolate this plagioclase component from the rock were not successful owing to the graphic intergrowth of the felspar with quartz, &c., but a few isolated fragments examined under the microscope gave straight extinctions on (010) and (001), indicating about 30 % of lime-felspar in the plagioclase.

Sections of the microperthitic microcline crystal ground on (010) and (001) are shown on pl. XIV, fig. 11. The perthitic structure is very regular for a microcline perthite, but much coarser than moonstone microperthite. The separation of the albite lamellae appears to have been more complete than in the moonstones even though the amount of soda component is less. This greater degree of separation is probably associated with the conversion of the felspar to microcline.

On (010) cleavage-flakes, the albite lamellae intersect the traces of the basal cleavage at an angle of 73°, showing that the lamellae have separated on the plane of moonstone schiller, which also appears to be the composition-plane of the pericline twins in this microcline.

In basal sections the majority of the albite lamellae lie along the lines of pericline twinning, i. e. parallel to the trace of (100), but a number of shorter lamellae run in a perpendicular direction, parallel to the trace of multiple albite twinning. The appearance of the section strongly suggests that the separation of the albite lamellae has followed immediately upon the microcline transformation. As will be shown later, the perthitic structure of this microcline is not destroyed by heating as it is in the case of moonstone felspar, nor is there any change in the microcline structure. The change into microcline is an irreversible one up to near the fusion-point of the felspar.

The specific gravity of the mineral is 2·5654 at 15° C., and the extinction on (010) is 6·2°. These figures are not appreciably altered by heating to 950°–1000° C. for six hours.

7. Schillerized Moonstones from other Localities.

Since the completion of the foregoing investigations on Ambalangoda moonstones, a number of schillerized alkali-felspars from other localities (Kandy, Burma, and Colorado) have been examined. These show a much wider range in soda and potash than the Ambalangoda specimens, and the relationship between chemical composition and physical properties can be studied in a manner not possible with the limited composition of the Ambalangoda specimens. I believe that it will be more instructive to give these later results in the order obtained rather than attempt to incorporate them with those of the Ambalangoda stones, even though this may involve some repetition. In addition to these, albites from India and Virginia have been examined for comparison and for the purpose of illustrating certain relationships between composition and physical properties of the alkali-felspars.

A. *Moonstone from Kandy, Ceylon.*

Some of the specimens examined were rough and uncut, others were cut and polished. They show a white schiller, exactly similar to that seen in the white variety of Ambalangoda moonstone. A cleavage-flake on (010) shows a fairly coarse, regular, microperthitic structure and the (Or, Ab) 'shadow' structure similar to the structures seen in white Ambalangoda specimens. The following results were obtained with two of these specimens.

	I, rough.	II, cut.
SiO_2	64·97	63·90
Al_2O_3	19·77	20·40
Fe_2O_3	0·23	0·60
FeO	—	trace
MgO	0·15	0·10
CaO	0·20	0·40
Na_2O	4·24	3·70
K_2O	10·42	10·67
Ign. loss	0·37	0·20
	100·35	99·97
Potash-felspar	62·8	65·4
Soda-felspar	36·2	32·5
Lime-felspar	1·0	2·1
	100·0	100·0
Extinction on (010) ...	10·5°	8·8°
Optic axial angle (2V) ...	72·1°	65·6°
Sp. gr. at 15° C.	2·5810	2·5832

It will be observed that the composition of the first lies very close to that of the white Ambalangoda moonstone, while that of the other is near that of the Ambalangoda blue stone.

B. *Moonstone from Mogok, Burma.*

In 1927 I collected four water-worn pebbles (*a*–*d*), each about an inch in diameter, from the gem-washing residues at the Mogok Ruby Mines, Northern Shan States, Burma. These residues appear to be derived from the weathering of pegmatites intruded into a country-rock of crystalline limestone.

It will be observed from the results below that a progressive increase in the proportion of soda-felspar is accompanied by a progressive increase in schiller intensity, in the extinction-angle, in the optic axial angle, and in the density. Each specimen will now be considered in detail.

(*a*) *Burma 'Colourless'*.—This specimen is glass-clear and shows absolutely no trace of schiller. The cleavage on (001) is perfect. On (010) the cleavage is not so perfect and the surface is slightly undulatory. Under the microscope the mineral shows no indication of microperthitic structure, even under optimum conditions of illumination, neither does the etching method described on pp. 357–361 indicate a laminated structure on the perthite plane Δ. This is in accord with the fact that the mineral contains less than 8 % of soda-felspar, which amount, as we have seen from the equilibrium diagram of C. H. Warren, and from an examination of the de-albitized Ceylon moonstones, is capable of being retained in solid solution in potash-felspar under normal equilibrium conditions. This ‘colourless’ stone and the remaining Burma felspar specimens possess the optical orientation of normal orthoclase, that is, the plane of the optic axis is perpendicular to the crystallographic axis *b*, and the optical sign is negative, as it is in Ceylon moonstone.

	(*a*) ‘Colourless without schiller.	(*b*) Faint blue schiller, I.	(*c*) Blue schiller, II.	(*d*) Strong white schiller.
SiO_2	63·66	65·30	65·14	64·02
Al_2O_3	19·54	18·84	19·60	19·58
Fe_2O_3	0·10	0·16	0·10	0·32
FeO	—	—	—	trace
MgO	—	—	—	0·16
CaO	0·50	0·34	0·45	0·33
Na_2O	0·80	1·62	2·20	3·02
K_2O	15·60	14·18	13·07	12·12
Ign. loss	—	—	—	0·28
	100·20	100·44	100·56	99·83
Potash-felspar	90·9	84·5	78·8	72·6
Soda-felspar	6·6	13·8	19·0	25·8
Lime-felspar	2·5	1·7	2·2	1·6
	100·0	100·0	100·0	100·0
Extinction on (010) ...	5·3°	6·2°	7·0°	7·7°
Extinction on (001) ...	0°	0°	0°	4·0°
Optic axial angle (2V)...	43·6°	46·2°	52·9°	61·1°
Sp. gr. at 15°C. ...	2·5632	2·5673	2·5712	2·5831

(*b*) *and* (*c*) *Specimens with Blue Schiller.*—These two specimens are glass-clear, with perfect cleavage (001), and less perfect, undulatory cleavage (010). They show traces of very fine (or, ab) microperthitic structure when seen on (010) cleavage-flakes under optimum conditions of illumination, but the (Or, Ab) shadow perthite appears to be absent. This would be expected from the composition of these two felspars. The proportion of soda-felspar present, although in excess of the solubility maximum for the (or) microperthite, is below that of the (Or) ‘shadow’ perthite phase. Hence the felspar, on cooling below the crystallization temperature, would remain one single solid solution down to the point of separation of the (or, ab) microperthitic structure.

The (or, ab) lamellae are more distinct than in the Ceylon blue stones, but their direction is more irregular. The irregularity appears to be associated with the absence of (Or, Ab) structure. The schiller and microperthitic structure are both destroyed by heating, but at lower temperatures than in the case of the Ceylon stones. The schiller is destroyed at 700°–800° C. and the microperthitic structure somewhere between 700° C. and 900° C.

Specimen (*b*), although possessing schiller and microperthitic structure, contains only 14 % soda-felspar, which is only 4–6 % more than the amount capable of being retained in solid solution under normal equilibrium conditions. From this it may be inferred that the conditions under which these Burma moonstones were formed (i. e. rate of cooling, presence of mineralizers, &c.) were very favourable to exsolution of the (or, ab) microperthite lamellae. This is also indicated by the white schiller and coarse microperthitic structure of the white Burma stone, which is relatively low in soda-felspar; indeed, considerably lower than that of blue Ceylon moonstone.

(*d*) *Specimen with White Schiller.*—This specimen shows a strong white schiller and is turbid or translucent in thick sections. The cleavage on (001) is perfect; it is less perfect on (010), but more perfect than in the blue stones or the 'colourless' specimen. Under the microscope the mineral exhibits a microperthitic structure very similar to that of the white Ambalangoda moonstone, except that the (or, ab) microperthite is somewhat coarser and less regular than in the latter. The microperthite lamellae (seen on (010) cleavage-flakes) show a greater tendency to deviate from the schiller plane into the direction of the *c*-axis than in the Ceylon variety. The (Or, Ab) 'shadow' perthite is also seen, but not so prominently as in the white Ambalangoda specimens.

In addition to these perthitic structures the sections show abundant minute inclusions of a mineral which appears to be tourmaline. The inclusions have the form of rods or needles about 0·03 mm. in length and 0·003 mm. in breadth. They lie mainly in the plane of (010). The microperthitic structure and the inclusions are shown on pl. XV, fig. 12, which represents a (010) cleavage-flake under crossed nicols, magnified 200 diameters.

This mineral shows an oblique extinction on (001) up to 4°, which is the highest extinction on (001) observed by me in moonstone felspar. Alling has suggested that these occasional oblique extinctions in potash- or potash-soda-felspars indicate that they are really pseudomonoclinic microclines. The Burma white specimen, however, shows no trace of microcline twinning either on cleaved or ground sections, and the same may be said of all the moonstone felspars I have examined. Further, the specific gravity and the behaviour under heat-treatment (as described on p. 345) are both more indicative of monoclinic than triclinic symmetry. If this moonstone is heated to a temperature of about 1050° C. for a few hours, the white schiller is reduced in intensity and the microperthitic structure is in large part destroyed.

C. *'Sanidine' from Ragged Mountain, Colorado.*

This interesting felspar was described by Whitman Cross (11) in 1885. It occurs as phenocrysts up to three inches in length and one inch in diameter in a medium-grained rhyolite. The following is an extract from the description by Cross of one of these phenocrysts:

> The section parallel to the lustre plane brings out still more distinctly a zonal structure which was visible in the crystal. The outer zone has a much more brilliant lustre than the interior, and certain parts of the latter are quite transparent. In these portions, when the satiny lustre of the outer zone is at its maximum brightness, a delicate pale-blue colour is visible like that of the Chalk Mountain sanidine.

From this description I was led to suspect that the Ragged Mountain phenocrysts might possibly contain, within a single crystal, the whole of the range from blue to white schiller of moonstone, with a corresponding increase in soda-felspar content from the centre outwards. It has been pointed out on p. 323 that phenocrysts of potash-soda-felspar separating from a magma originally low in soda, might show a zoned structure with an increase in soda-felspar content towards the outside of the crystal. Such a zoned felspar on cooling below the solidus line would, by exsolution of the albite, develop a microperthitic structure, first in the outer zones of the crystal, then later (and progressively finer in texture) towards the centre, with a corresponding graduation of schiller colour.

A portion of one of these Ragged Mountain phenocrysts and of the parent rhyolite were presented to me by Dr. Whitman Cross for examination. Cut parallel to the lustre or schiller plane, the crystal, which is a Baveno twin, shows sharply alternating schiller zones varying from $\frac{1}{16}$ (or less) to $\frac{1}{4}$ inch in breadth (pl. XV, fig. 13). The broad zones show pearly to satiny white schiller, the intervening zones being clear to pale blue. This alternate schiller-zoning suggests an oscillation in composition of the felspar in successive zones, rather than the expected progressive increase in soda-content from the centre of the crystal outwards.

A section cut parallel to the plane (010) shows the zones to consist of alternate areas or bands of coarse and fine microperthite of the white and the blue moonstone types respectively. The areas are very clearly divided in places, the boundary between coarse and fine microperthite cutting sharply across, and almost perpendicular to, the direction of the (or, ab) lamellae (pl. XV, fig. 14). This in itself is very strong evidence in support of the view that these microperthitic structures are of post-crystallization, or exsolution, origin. In the coarser areas, incipient decomposition has accentuated the visibility of the microperthite and the intensity of the schiller.

The extinction on (010) sections varies from about 9° to 10° in the coarsely perthitic areas down to about 7° in the clearer zones. It will be seen by reference to fig. 4 that this variation in extinction-angle indicates a fluctuation in the soda-felspar content from about 12 to 30 %.

The specific gravity of different fragments of the crystal varies between 2·571 and 2·574 at 15° C. The chemical compositions of the zoned crystal and of the parent rock are shown below:

	Baveno twin crystal.	Rhyolite rock.
SiO_2	63·26	63·88
Al_2O_3	20·38	18·56
Fe_2O_3	0·32	1·04
FeO	—	2·52
MgO	0·44	1·34
CaO	0·56	4·34
Na_2O	2·74	3·68
K_2O	11·74	3·34
Ign. loss	1·00	1·30
	100·44	100·00
Potash-felspar	72·9	27·2
Soda-felspar	24·1	42·9
Lime-felspar	3·0	29·9
	100·0	100·0

As would be expected from a rhyolite of the above composition, a section shows an abundance of plagioclase crystals. They occur as zoned phenocrysts, together with zoned alkali-felspar in a microcrystalline groundmass. In addition to the felspar, the rock contains a fair amount of idiomorphic hornblende, mica, some magnetite, and a little free quartz. Of the felspars, only the alkali members show schiller and microperthitic structure. In some of the alkali-felspar phenocrysts small inclusions of plagioclase may be seen.

D. '*Sanidine*' *from Chalk Mountain, Colorado.*

This felspar and its parent-rock were described along with the Ragged Mountain sanidine by Dr. Whitman Cross, to whom I am indebted for samples. The rock, which in the original description is termed a 'nevadite' (13), has a light-grey colour and contains porphyritic crystals of smoky-quartz and of felspar up to $\frac{1}{4}$ inch in diameter, embedded in a microcrystalline groundmass. The rock is almost devoid of ferromagnesian minerals.

The felspar is clear in thin sections, but translucent to opaque in crystal fragments, owing to partial kaolinization. Some of the clearer phenocrysts show a white to blue-white schiller on surfaces broken approximately parallel to the schiller plane Δ.

A rock section shows the felspar phenocrysts to be orthoçlase and plagioclase (albite), the latter being present in relatively small proportion. The groundmass is microcrystalline. Many of the orthoclase crystals show plagioclase in parallel intergrowth, indicating that the two felspars have grown simultaneously. Zoning is common in the orthoclase, with an increase in refractive index and extinction-angle on (010) towards the outside of the crystal. Some of the sections parallel to (010) show a fine regular microperthitic structure, with the same regular bands or patches of coarser perthite described in the Ragged Mountain orthoclase, due to zones richer in albite. The direction of the lamellae makes an angle of 73° with the trace of (001). The albite phenocrysts appear to be free from schiller and microperthitic structure.

In order to isolate the felspars for separate examination, a portion of the rock was coarsely crushed, washed, and hand-picked. The felspar fragments were then separated by a bromoform mixture into three crops. The heaviest or albite crop, with a specific gravity of about 2·62, and the lightest potash-soda or orthoclase crop of specific gravity 2·57, were reserved for physical and chemical tests.

(*a*) *Albite Crop.*—A number of fragments from this crop were ground on the face (010) and the mean extinction was found to be about 18·5°. Sections on (001) showed an extinction of 3·5° to 5° and the usual lamellar twinning of albite. All the fragments appeared to be free from schiller. An idiomorphic albite crystal of specific gravity 2·625 was selected from this crop for a heat-treatment test.

(*b*) *Soda-orthoclase Crop.*—The fragments in this crop possessed a white to blue-white schiller. The whiteness of the schiller has been accentuated by partial decomposition along the schiller plane. Cleaved fragments on (010) and (001) showed in places the fine (or, ab) microperthite and some evidence of (Or, Ab) ‘shadow’ perthite. Sections ground on (010) gave a mean extinction of 8·3°. The extinction on (001) is straight. Some of the sections show Carlsbad twinning.

The chemical composition of the two felspar crops and of the parent nevadite are given below. Analyses by Hillebrand (13) of the nevadite and of a ‘sanidine’ phenocryst from the same are added for comparison.

	Nevadite Rock.	Albite Crop.	Orthoclase Crop.	Nevadite (Hillebrand).	‘Sanidine’ (Hillebrand).
SiO_2 ...	72·66	63·96 (diff.)	66·89 (diff.)	74·45	65·04
Al_2O_3 ...	15·31	23·54	17·78	14·72	20·40
Fe_2O_3 ...	0·25	trace	trace	0·56	—
FeO ...	0·36	—	—	—	—
MnO_2 ...	0·12	—	—	0·28	—
MgO ...	0·55	—	—	0·37	—
CaO ...	1·31	0·68	0·65	0·83	0·79
Na_2O ...	3·61	10·32	3·76	3·97	4·11
K_2O ...	4·54	1·50	10·92	4·53	9·74
Ign. loss	1·39	—	—	0·66	0·29
	100·10	100·00	100·00	100·37	100·37

The composition of the rock is very similar to that of the Ambalangoda pegmatite-rock and to that of the Sparling Gulch rock (p. 338). In all three cases the magma was, to all intents and purposes, a straight alkali-felspar–silica mix, with a subordinate amount of lime-felspar and possibly gaseous and liquid mineralizers in addition. The ratio of potash- to soda-felspar in this rock is about 47 to 53, which is so close to the felspar ratio in the Ambalangoda rock that the composition line P–P_0 (fig. 3) may also be taken to represent the Chalk Mountain magma.

Thus the first crystals to separate from this magma (p. 327) would be orthoclase with about 30 % of soda-felspar, followed by crystals or crystal zones richer in soda-felspar up to 40 %. Further crystallization would then yield simultaneously two felspars of composition: (*A*) soda-orthoclase with 40 % soda-felspar; (*B*) albite with 88 %

soda-felspar. It has been suggested (p. 324) that in the presence of the other components, such as quartz and mineralizers, these two felspars of binary eutectic composition *A* and *B* might continue to separate as phenocrysts, with possibly quartz, until the excess of these components over *the ternary or quaternary eutectic* had been eliminated.

That crystallization in the Chalk Mountain nevadite closely followed these lines is indicated by the following points:

(*a*) The presence of phenocrysts of soda-orthoclase, albite, and quartz, the two felspars having compositions close to those indicated by the points *A* and *B* of the immiscibility gap of fig. 3. Thus, according to this diagram, the average composition of the soda-orthoclase phenocrysts separating between P–P_0 and *A*, and of the albite crystals separating at the point *B* would be:

	Soda-Orthoclase.	Albite.
Potash-felspar	63 %	12 %
Soda-felspar	37	88

The actual composition of these two felspars calculated from the analyses are as follows:

	Soda-Orthoclase.	Albite.
Potash-felspar	66·5 %	10·5 %
Soda-felspar	33·5	89·5

(*b*) The zoned character of many of the soda-orthoclase phenocrysts, the increase in soda being towards the outside of the crystal.

(*c*) The microperthitic structure and schiller in the soda-orthoclase phenocrysts produced by exsolution below the solidus line. The albite phenocrysts appear to have retained the potash-felspar in solid solution, since microperthitic structure and schiller are absent from these crystals.

E. *Blue Moonstone in Rhyolite from Sparling Gulch, Colorado.*

A specimen of this interesting rhyolite was also presented to me by Dr. Whitman Cross. It is a grey, fine-grained, crumbly rock, containing small felspar crystals up to $\frac{1}{8}$ inch in diameter. These crystals possess a beautiful blue schiller. A section of the rock shows phenocrysts of orthoclase felspar embedded in a microcrystalline groundmass. Some of the crystals are twinned on the Carlsbad law. Phenocrysts of quartz up to $\frac{1}{16}$ inch in diameter are also plentiful. Biotite occurs in small quantity. Albite appears to be absent.

The orthoclase phenocrysts exhibit a coarse (or, ab) microperthitic structure on sections nearly parallel to (010) and in some the (Or, Ab) ‘shadow’ structure also shows faintly. The microperthite is coarser and less regular than that seen in the blue or white Ceylon moonstone. There is also a distinct tendency for the microperthite to become coarser and less regular towards the outside of the crystals and for individual microperthite lamellae to project irregularly beyond the crystal into the groundmass, thus giving a serrated edge to the crystal boundary as seen under high magnification. Most of the orthoclase phenocrysts show a narrow outer zone of felspar interstitial to the groundmass but in optical continuity with the crystal and extinguishing simultaneously with it.

The orthoclase phenocrysts can be readily separated from the much softer rock-matrix by gentle crushing, washing, and hand-picking. Fragments of these crystals cleaved and ground on (010) gave extinctions of 9·5° to 10·5°. The extinction on (001) varied from 0° to 3°. No sign of lamellar twinning was observed on any of these sections. In sections on (010) the trace of the microperthite lamellae intersects the trace of (001) at an angle of about 73°. If the samples are heated for some time to 1000° C., the blue schiller and the microperthitic structure are destroyed.

The specific gravities of the phenocrysts range from about 2·575 to 2·582, with the majority about 2·578. A batch of crystals of specific gravity 2·578 was taken for analysis and heat-treatment tests. The composition of these phenocrysts and of the rhyolite rock is given below:

	Crystals.	Rhyolite.
SiO_2	67·48	73·54
Al_2O_3	18·42	14·70
Fe_2O_3	0·40	0·80
FeO	—	trace
MgO	0·20	0·24
CaO	0·73	0·53
Na_2O	5·25	4·00
K_2O	7·87	5·88
Ign. loss	0·22	0·43
	100·57	100·12

The analysis of the felspar phenocrysts shows an excess of silica over that required for the felspars, the total felspar being only 94 %. This is probably due to adherent fragments of the groundmass. If we calculate the alkali-felspars in the crystals and in the rhyolite to 100 %, the ratios are practically the same for both:

	Orthoclase Phenocrysts.	Rhyolite.
Potash-felspar	51·3 %	50·7 %
Soda-felspar	48·7	49·3

We may compare these results with those of the crystallization of the Chalk Mountain and the Ambalangoda magmas, which possessed very nearly the same composition. In the latter case, cooling has resulted in the simultaneous crystallization of soda-orthoclase and of albite, the compositions corresponding very closely to the points *A* and *B* of the immiscibility gap on fig. 3. In the case of the Sparling Gulch rock, a single crop of small soda-orthoclase phenocrysts of fairly uniform composition has separated with the same alkali-felspar ratio as that in the original magma. Here the immiscibility gap is negligible and the equilibrium diagram of Dittler is in better agreement with the separation than that of Vogt and Warren.

The two principal factors which might have contributed to this difference in behaviour of the magmas are: (*a*) the slower rate of cooling of the Chalk Mountain and Ambalangoda magmas; and (*b*) the presence of gaseous or liquid mineralizers which have since disappeared. Of the two, I believe that the more rapid rate of cooling of the Sparling Gulch magma has been the principal cause of the difference in results. This view is supported by the following facts:

(*a*) The phenocrysts are much smaller in size and the rock is of finer grain than the Chalk Mountain specimen.

(*b*) The blue schiller is abnormal for moonstone with 50 % of soda-component. Most moonstones with more than 40 % of soda-felspar tend to possess a white schiller and a coarse microperthitic structure.

(*c*) As will be seen later, the mean extinction-angle, the specific gravity, and the optic axial angle are all abnormal for these felspars. These facts and the anomalous blue schiller all indicate incomplete exsolution due to rapid cooling.

It will be evident that if some retarding influence, such as rapid cooling, is essential for the formation of moonstone abnormally high in soda, that is, with a composition lying within the immiscibility range of fig. 3, there will always be a tendency for such felspars to show incomplete exsolution of the (or, ab) structures. The same operative causes which tend to prevent separate crystallization of the two phases of composition *A* and *B* in the upper regions of the equilibrium diagram will, in general, be active in retarding exsolution of the perthite in the lower, or solidus area, of the diagram.

F. *Albite Specimens.*

These two specimens were selected to represent the soda-felspar end of the alkali-felspar series.

Albite from Raipura, Orissa, India.—In an earlier paper (27) I have given a description of this felspar. It occurs as twin-crystals up to about ½ inch in length, embedded in a sedimentary limestone. The felspar is opaque to translucent and free from schiller. Small, fairly clean, cleavage pieces were taken for testing.

Albite from Amelia, Virginia.—A few small tabular fragments of this felspar were obtained from the Geological Survey of India for examination. The crystals are translucent and white to glass-clear. The composition of this felspar is given in Iddings's 'Rock Minerals' as Ab_{100}, but my specimen contained small amounts of both lime and potash.

	Albite, Raipura.	Albite, Amelia.
SiO_2	66·95	67·24
Al_2O_3	19·72	20·48
Fe_2O_3	0·37	0·12
FeO	0·10	—
MgO	0·88	—
CaO	0·66	0·25
Na_2O	9·95	11·43
K_2O	0·52	0·44
Ign. loss	0·63	0·30
	99·78	100·26
Potash-felspar	3·3	2·6
Soda-felspar	93·2	96·3
Lime-felspar	3·5	1·1
	100·0	100·0
Extinction on (010)	18·6°	18·8°
Optic axial angle (2V)	80·5°	79–82·5°
Specific gravity at 15° C.	2·625	2·627

8. Relation between Physical Properties and Chemical Composition in these Schillerized Felspars.

A. *Composition and Extinction on (010).*

Reference has already been made on p. 305 to Bøggild's attempt to deduce a progressive relationship between the extinction-angle and chemical composition of schillerized potash-soda-felspars. The exceptions to this relationship noted by him were probably due to the fact that the extinction-angle and the chemical composition were not always determined on the same sample.

The schillerized felspars described in the foregoing pages show a definite progressive relationship between extinction-angle and chemical composition (fig. 4). It will be observed that most of the specimens fall on, or close to, the straight line *PT* drawn through the Burma 'colourless' and the albite specimens. This line represents the 'additive' law which the extinction-angles of these perthitic felspars ought to follow if exsolution of the albite member is complete. The equation $x = 100\ (\mathrm{E} - 4°)/15$, where x is the percentage of soda-felspar and E° is the extinction on (010), approximates to this straight-line relationship. Two specimens show a marked deviation from the straight-line relationship. One is microcline with 22 % of soda-felspar. This mineral possesses triclinic symmetry, and obviously it does not belong to this microperthitic moonstone felspar series. The other is Sparling Gulch moonstone with 50 % of soda-felspar; it has already been mentioned that exsolution in this specimen is probably incomplete.

B. *Specific Gravity and Composition.*

In fig. 5, plotting the specific gravity and the soda-felspar content, it will be noted that for most of the felspars a straight-line relationship here also exists. The microcline and Sparling Gulch specimens, however, again show a distinct departure from the straight line of complete exsolution; while Ambalangoda moonstones show a slight deviation, the specific gravities in these cases being lower than the normal.

A marked deviation in the opposite direction is shown by Burma White and Kandy White II specimens. In the Burma specimen the higher specific gravity is explained by inclusions of microscopic tourmaline. The calculated quantity of tourmaline necessary to cause this deviation is about 2 %. If the deviation of the Kandy specimen is due to a similar cause, the inclusions necessary to give this deviation would amount to less than 1% and the included mineral might not be visible under the microscope. Faint indications of such inclusions were observed, however, on examining sections of the Kandy stone under high power, but the most positive ocular evidence that the mineral contains sub-microscopic inclusions is furnished by the peculiar oily or smoky appearance of the specimen when viewed through

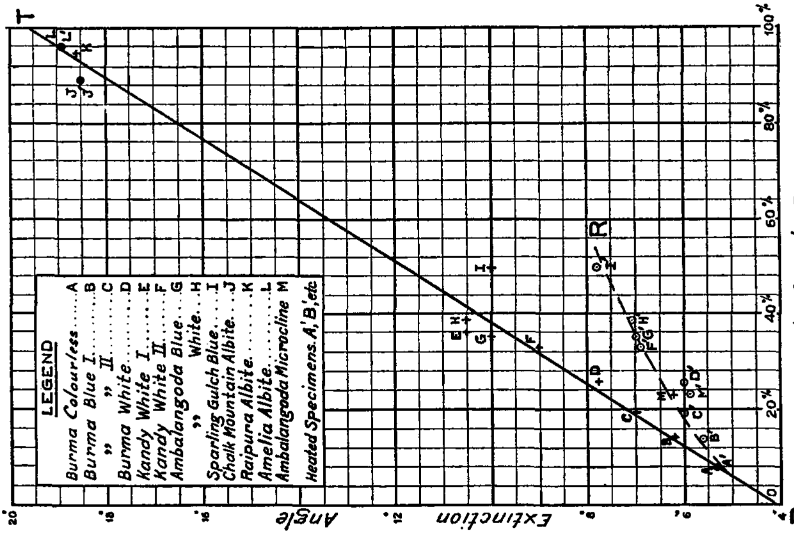

FIG. 4. Extinction on (010) and composition of alkali-felspars.

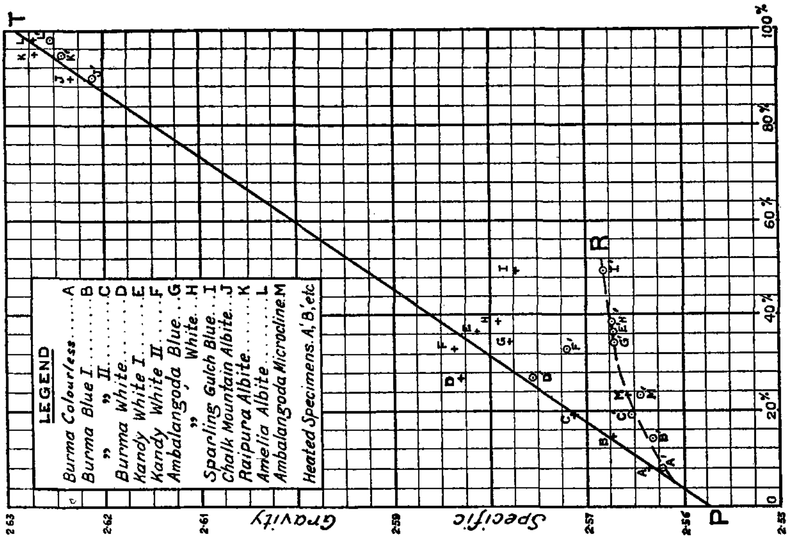

FIG. 5. Specific gravity and composition of alkali-felspars.

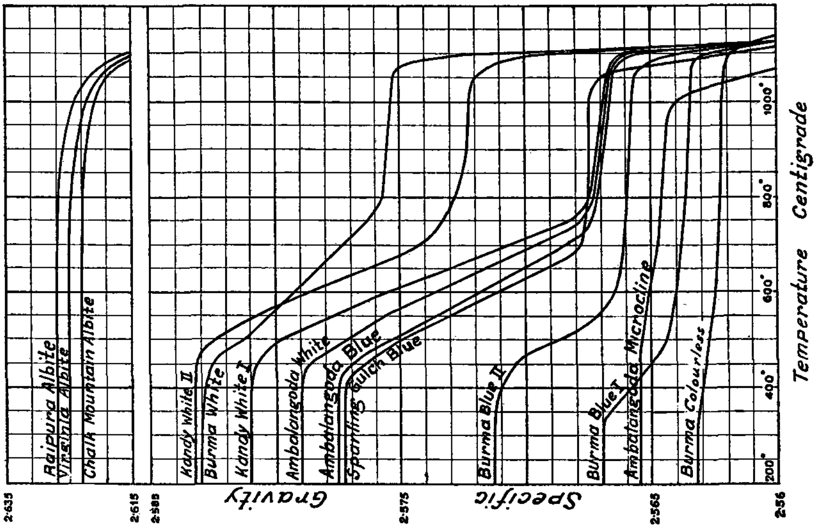

FIG. 7. Specific gravity changes by heating in alkali-felspars.

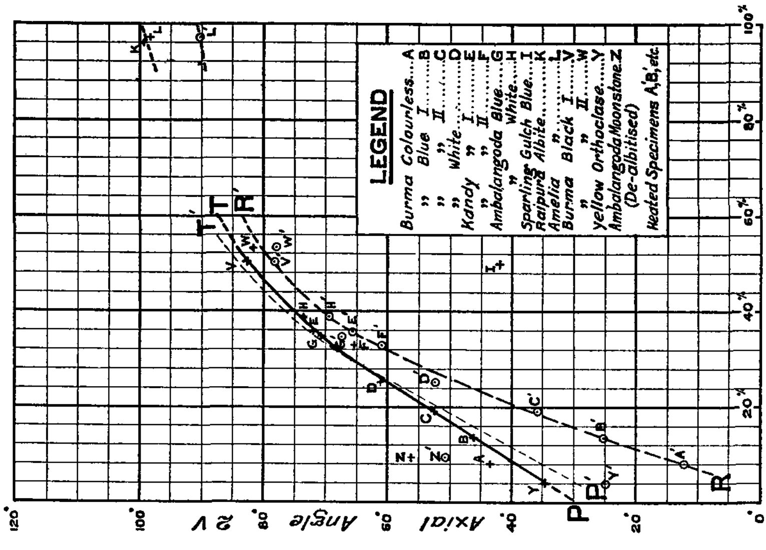

FIG. 6. Optic axial angle and composition of alkali-felspars.

(010) or (001) cleavage-faces. As will be seen in the following pages, the two last-mentioned specimens show a normal diminution in specific gravity on heating.

C. *Optic Axial Angle and Composition.*

A similar progressive relationship exists between the angle of the optic axes and the composition of these felspars, as will be seen from a reference to curve *PT*, fig. 6. On this curve three additional specimens have been introduced. These indicate the trend of the curve beyond the limits of the specimens previously described. A complete examination of these specimens has not yet been made, but their approximate composition is shown below, together with their specific gravities, extinction-angles, and optic axial angles.

	Burma Black I (white schiller).	Burma Black II (blue schiller).	Yellow Orthoclase, Madagascar.
SiO_2	n.d.	n.d.	n.d.
Al_2O_3	19·96	19·58	18·78
Fe_2O_3	0·08	0·08	0·62
FeO	trace	trace	0·09
MgO	trace	trace	trace
CaO	0·84	0·84	trace
Na_2O	5·54	5·88	0·46
K_2O	8·12	7·64	16·14
Ign. loss	0·54	0·56	n.d.
Potash-felspar	48·4	45·6	96·0
Soda-felspar	47·4	50·2	4·0
Lime-felspar	4·2	4·2	trace
	100·0	100·0	100·0
Extinction-angle	11·7°	11·6°	5·0°
Optic axial angle (2V)	82·8°	81·75°	34·8°
Specific gravity	2·5950	2·5960	2·5625

Both the above-mentioned Burma specimens contain small rod-like inclusions similar to those previously described in the Burma White specimen. These inclusions, and the higher lime-content, probably account for the slightly abnormal specific gravity. Apart from this, the three specimens fit the specific gravity and extinction curves of figs. 4 and 5 fairly well, but the position of the yellow orthoclase suggests that for felspars with less than 10 % of soda the relationship is better expressed by a continuation of the line *PR* rather than *PT*.

To return to the optic axial angle, it will be seen that most of the points of fig. 6 lie close to the curve *PT*, which approximates to a straight line up to about 30 % of soda-felspar. With higher soda-content than this, the optic axial angle does not increase proportionately to the increase in soda-felspar, the curve bending round towards the composition axis and towards the position of the Amelia albite and Raipura albite specimens. (In these latter specimens the optic axes have widened out beyond 90°, the acute bisectrix emerging nearly perpendicular to the plane (010). For conformity, the obtuse axial angles have in these cases been plotted.)

As in the extinction and specific gravity curves, the Sparling Gulch specimen again provides an exception, the departure being, as before, towards the composition axis. The value of 2V, for various Sparling Gulch phenocrysts examined, ranges from about 38° to 44°.

Another exception to the curve is that of de-albitized felspar. The divergence of this specimen from the 'normal' is peculiar in view of the fact that the corresponding unaltered Ambalangoda specimens (G and H) lie close to the curve. It would almost seem as if the (or) lamellae have been partly reconstituted to an adularious[1] form of orthoclase during the de-albitization process.

If the relationship represented by the curve *PT* of fig. 6 should be found to hold for schillerized felspars in general, the optic axial angle would have a much greater determinative value than the extinction-angle or specific gravity, because of the wide variation of 2V with the composition. In all these schillerized perthitic felspars the obtuse bisectrix is perpendicular to the (010) cleavage and the plane of the optic axes is inclined at a small angle to the trace of the basal cleavage. Hence an optically oriented section can readily be obtained and, with the aid of a stage-goniometer and an oil of suitable refractive index, the observer can determine in a few minutes the value of 2V to within one or two degrees.

9. Effect of Heat-treatment on the Extinction-angle, Optic Axial Angle, and Specific Gravity.

We have already seen (p. 318) that the schiller colour and perthitic structure of Ceylon moonstone can be destroyed completely or in part, by heating for some time to temperatures between 750° and 1050° C. and again cooling. At the same time, the extinction-

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[1] The term adularious is here used in the sense of orthoclase of hydrothermal origin. A sample of non-schillerized adularia from St. Gotthard was found to have an approximate composition $Or_{90}Ab_{10}An_{tr}$ and 2V about 62°.

angle, the optic axial angle, and the specific gravity are reduced. Similarly, with the schillerized Mogok and Colorado felspars, the schiller and microperthitic structure can be partly or completely destroyed by heat-treatment. As in the Ceylon specimens, the schiller and microperthitic structure are more easily destroyed in the blue or blue-white specimens than in the felspars with white schiller.

A. *Effect of Heating to 950–1100° C. for 6 Hours.*

The changes in the extinction-angle, specific gravity, and optic axial angle brought about by heating these specimens for 2 to 6 hours to a temperature a little below the first point of incipient fusion (which varies between 900° and 1070° C. for different specimens) are shown in tabulated form below, together with the corresponding figures of untreated specimens for reference.

	Extinction (010).		Optic axial angle (2V).		Specific gravity.	
	Ordinary.	After heating for 6 hours at 1050–1070° C.	Ordinary.	After heating for 6 hours at 1050–1070° C.	Ordinary.	After heating for 2 hours at 900° C.
Ambalangoda White ...	10·5°	7·5°	73·3°	69·5°	2·579	2·5670
Ambalangoda Blue ...	10·0	7·5	70·5	67·0	2·5775	2·5670
De-albitized specimen ...	5·4	5·4	56·5	50·5	—	—
Ambalangoda Microcline	6·2	5·9	—	—	2·5654	2·5646
Kandy White I	10·5	—	72·1	66·0	2·5810	2·5670
Kandy White II... ...	8·8	6·9	65·6	60·8	2·5832	2·572
Burma 'Colourless' ...	5·3	5·3	43·6	12	2·5632	2·5622
Burma Blue I	6·2	5·6	46·2	25	2·5673	2·5635
Burma Blue II	7·0	6·0	52·9	35·8	2·5712	2·5658
Burma White	7·7	6·0	61·15	52·8	2·5831	2·5752
Burma Black I	11·7	—	82·8	78·6	2·5950	—
Burma Black II... ...	11·6	—	81·75	77·8	2·5960	—
Raipura Albite	18·6	18·6	80·5	—	2·625	2·620
Amelia Albite	18·8	18·8	81·2	88·0	2·627	2·623
Chalk Mountain Albite...	18·5	18·5	—	—	2·623	2·621
Sparling Gulch Blue ...	10·0	7·8	42·0	—	2·577	2·5675
Yellow Orthoclase ...	5·2	5·2	34·8	25·0	2·5625	2·5625

The values for the heat-treated specimens have been plotted on figs. 4, 5, and 6. The points within the circles represent the heat-treated specimens, the untreated specimens being represented by crosses on the same ordinates.

Changes in Extinction and Specific Gravity.—The curves *PR* of figs. 4 and 5 show the effect of heat-treatment on the extinction-angle and specific gravity respectively. It will be observed that the intermediate schillerized perthitic felspars with up to 40 % of soda-component all show a reduction in extinction-angle and specific gravity by an amount roughly proportional to the quantity of the perthitic soda-felspar present, while the non-perthitic felspars at the two extremes of the composition range retain their extinction-angles and specific gravities almost unchanged by the heat-treatment. The Burma 'Colourless' specimen remains practically unchanged in this respect after being heated for 12 hours to 1100° C., and the same applies to the Amelia and Raipura albites, after being heated for 6 hours to 1050° C. This does not, of course, preclude the possibility of some modification having taken place in these felspars, which lie at the ends of the series. As will be seen later, the optic axial angle of these specimens does suffer a change on heating to the above temperature.

Merwin (21), from an examination of the changes in double refraction on heating, found that albite and orthoclase both suffered an inversion (from a β-form to an α-form) on being heated to temperatures above 900° C., the transition in both cases being very sluggish. The β-form of orthoclase corresponds to adularia, and the α-form to sanidine. Winchell (31) has made these transformations a basis for classification. He assumes that Merwin's α-form of albite corresponds to the monoclinic form barbierite.

Although there appears to be no change, short of incipient fusion, in the extinction-angle and specific gravity when the Burma 'Colourless' orthoclase is heat-treated, the same cannot be said of the Amelia albite specimen. Prolonged heating at a temperature near 1100° C. causes a marked reduction in the extinction-angle, but the specific gravity remains practically unaltered. The change is heralded by the extinction becoming patchy; this is rapidly followed by a reduction in the average extinction in the patchy areas, the lowest extinction measured being about 10–12°. The corresponding change in Raipura albite is much more sluggish than in the specimen from Amelia, and a sample of schillerized oligoclase from near Kingston, Ontario, of ascertained composition $Ab_{85}Or_9An_6$, showed practically no reduction in extinction or specific gravity after being heated for 12 hours to 1100–1120° C.

Has this change in the form of albite any bearing on the changes which take place in the schillerized intermediate perthitic members? It may be that the final stages of the reduction in extinction-angle are due to the albite tranformation, but this cannot be responsible for the earlier stages of reduction in extinction, or for any part of the change in specific gravity, since the former commences and the latter is completed, below a temperature of 800° C. These relatively low temperature-changes appear to be associated entirely with the re-solution of the (or, ab) perthite to form the (Or, Ab) phases.

It is interesting to compare the two extinction lines of fig. 4 with the tentative extinction lines drawn up by Winchell (31). The curve *PR* (fig. 4) representing the heat-treated specimens, corresponds fairly closely with Winchell's sanidine-barbierite extinction curve, and the modified extinction figure (10° to 12°) for heat-treated Amelia albite referred to on p. 347 would lie on the curve *PR* produced. Winchell's tentative extinction curve for the adularia-albite series shows a sharp upward bend, but if the correction suggested on p. 306 were applied, the curve would become straight and coincident with the lower part of curve *PT* (fig. 4.) which represents the untreated specimens. It will be evident that if the curve *PT* represents the extinction line of complete exsolution and *PR* the approximate position of the curve of complete solution as one homogeneous phase (sanidine-barbierite series), then all the possible extinction-angles of these two series of potash-soda-felspars are comprised between the two curves, the proportional amount of divergence from *PR* towards *PT* being a measure of the degree of exsolution of the (or, ab) microperthite or cryptoperthite. The same applies to the specific gravity curves of fig. 5.

Changes in Optic Axial Angle.—The curve *RR′* of fig. 6 shows the effect on the optic axial angle of heating the specimens for six hours at 1050–1070° C. It will be observed that the greatest change is now in the felspars near the potash end of the series, the smallest change occurring in those specimens with 40 to 50 % of soda-felspar.

With longer heating times or higher temperatures, the curve *RR′* approaches nearer to the composition axis. For temperatures of the order of 650–850° C., the optic axial angle of specimens with more than 25% of soda-felspar appears to increase slightly,[1] while for those with less than 25% of soda-felspar, the optic axial angle is reduced. The curve *P′T′* represents, approximately, the results of heating various specimens to 800° C. for one hour.

Specific Gravity Fall and Composition.—The difference in specific gravity between heated and non-heated specimens appears to be a

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[1] Kôzu (17) has observed an increase in the optic axial angle of Ceylon moonstone on heating between 600° and 900° C.

much better guide to the composition than does the true specific gravity, and this relationship might be of use as a rough check on the composition of these felspars. The measurement of a fall in specific gravity is very much simpler than the determination of true specific gravity to the required degree of accuracy, as will be seen if one refers to the method described on pp. 352–3.

If d is the difference in specific gravity of the heated and non-heated fragments, then the approximate percentage of soda-felspar in the moonstone is given by $(3000d+8)$, or if T° C. is the temperature-difference of suspension of the two fragments in the bromoform-benzene mixture, the approximate percentage of soda-felspar is given by $6\mathrm{T}+8$.

This method cannot be expected to give more than a rough approximation to the composition. It may serve, however (in conjunction with the extinction-angle and optic axial angle), as a valuable check on the assumption, often made, that moonstones from the same locality are similar in composition. In those moonstone felspars of which the composition is accurately known, and the extinction-angle and specific gravity difference, after heating, are below the calculated values, the discrepancy may be taken as a good indication of incomplete exsolution.

It should be remembered that the above relationship has only been shown to hold for schillerized felspars with 40 % or less of soda-component. Since the change in specific gravity on heating is completed at a temperature well below that at which albite is affected (and below Merwin's β- to α-transformation temperature for this felspar), it will be evident that there must be some composition, above 40% and below 100 % of soda-component, at which the fall in specific gravity on heating to temperatures of 800–900° C. ceases to be even approximately proportional to the amount of soda-perthite present, that is, some point at which the curve *PR* begins to bend upwards towards the point *T* (fig. 5). Whether for these heating temperatures the curve *PRT* is disjointed, or continuous, remains to be seen. An examination of schillerized felspar with more than 40 % soda-content would probably throw light on this question.

Although the specific gravities of the Burma White and Kandy White II specimens are anomalous, the fall in specific gravity when they are heat-treated corresponds to the amount expected from their soda-felspar content, that is, the heat-treated specimens lie about the same distance above the curve *PR* as the untreated specimens lie above the line *PT*. This tends to confirm the suggestion that their anomalous position on the specific gravity chart is due to inclusions or at least to some cause independent of perthitic structure.

It is interesting to note that the extinction-angle and specific gravity of the untreated microcline specimen lie approximately on the lower curve *PR*, corresponding to the heat-treated schillerized or moonstone felspars, and that these values for microcline remain practically unchanged by heat-treatment.

The anomalous behaviour of the Burma White and Kandy White II specimens illustrates the necessity, in this work, of ensuring that the felspars examined are in all cases uniform in composition and that the physical tests and chemical analyses are always carried out on the same sample. Had the Ceylon and Burma specimens not been remarkably fresh and uniform in composition, the relationships now observed would probably have been obscured by a maze of anomalies. This is evident immediately one turns to ordinary rock felspars. I will take only two examples, namely, labradorite (Ontario) and microcline (Hazaribagh, India), out of a number of anomalous rock felspars examined. These showed for different fragments of *the same crystal* a variation in specific gravity wider than the whole range of the schillerized potash-soda felspars examined. Specimens of the Hazaribagh microcline, however, sorted into batches by bromoform mixtures, confirmed the behaviour of the more uniform Ambalangoda microcline in that no appreciable loss in specific gravity occurred on heating to 900–1000° C.

B. *Effect of Progressive Heat-treatment.*

The change in specific gravity in these schillerized felspars by heat-treatment is more rapid than the changes in extinction-angle, optic axial angle, and perthitic structure. Thus, while it may take several hours at a temperature of 1000–1070° C. to destroy the greater part of the perthitic structure and reduce the extinction-angle to a minimum, the change in specific gravity is almost completed in a few minutes at a temperature of about 800° C. Until incipient fusion commences, an increase in the time or the temperature produces little further effect on the specific gravity.

This smallness of ‘ lag ’ in the change of specific gravity with temperature and the ease with which small changes in specific gravity can be measured, allow of a fairly accurate determination of the temperatures at which the change takes place. By heating specimens for one hour at successive temperatures of 250°, 300°, 350°, &c., up to near the fusion-point of the felspar, the curves shown on fig. 7 were obtained.

The temperature at which the specific gravity of the schillerized perthitic felspars is first affected depends to some extent on the composition. The felspars lowest in soda are the first to change. The Burma specimen Blue I, for example, with 1·7 % of soda, begins to take on a permanent expansion at about 350° C., while the corresponding change in Ceylon moonstones, with 4 % of soda, takes place at about 500° C. The change in permanent expansion for most of the specimens commences at about 450–500° C. In the two Burma specimens I and II the permanent change in specific gravity is nearly completed at 550° and 600° C. respectively, but in the remaining specimens, with higher soda-content, the change is not complete until a temperature of 750° or 800° C. is reached. This change-gradient in the specific gravity is, however, to some extent a function of time. It was found, for example, that a specimen of Ceylon blue stone which had been heated for one hour at 550° C. fell 0·002 in specific gravity on being again heated at that temperature for a further four hours, whereas on the flat part of the curve, between 800° and 1000° C., no such change in specific gravity with time was observed. Thus, the sloping part of the curves, between 350° and 800° C., would have been a little steeper had a longer heating-time been chosen, and the same applies to the change in specific gravity above 1000° C.

Between the temperatures of 800° and 1000° C. there is very little further change in specific gravity. At temperatures above 1050° C. the specific gravities of the schillerized felspars begin to fall away rapidly. In the albite and microcline specimens the change begins just below 1000° C.; and in the moonstones with high soda-content, such as the Sparling Gulch and Ceylon specimens, the change commences at about 1050° C. For the Burma Blue specimens the temperature is a little higher, and for Burma 'Colourless' the change does not begin until near 1100° C. For a given temperature and heating-time the fall is most rapid with those moonstones high in soda, and most gradual in the case of the Burma 'Colourless' stone, which is low in soda.

Although this rapid fall in specific gravity begins at temperatures well below the first microscopic indications of incipient fusion (and 100–150° C. below the temperature of true fusion as measured by the destruction of cleavages and the production of opacity, &c.), there is little doubt that the steep downward bend of the curve marks the incipient stages of fusion. From this point the drop is continuous and increasingly rapid up to the melting-point of the felspar. If this inflection point of the curve is taken as a guide to the fusibility of these felspars, it follows that albite and microcline microperthite are the most fusible, the high-soda moonstones come next in order of fusibility, then the low-soda moonstones and the non-schillerized Burma 'Colourless' last.

C. *Measurement of Specific Gravities.*

To measure these progressive changes in density, it is necessary to be able to measure differences in specific gravity readily to the order of 0·001. It may be of interest to give a brief outline of the method I adopted to measure these small differences.

A number of specimens, including Burma and Ceylon moonstone and Amelia albite, were selected to cover the specific gravity range, and the true specific gravities of these were determined in the ordinary way by weighing large clear pieces in air and water. Each result was checked on a small fragment from the same specimen by weighing a specific gravity bottle containing the specimen and filled with a bromoform-xylene mixture so adjusted that the specimen remained in suspension in the liquid at the temperature of weighing. These specimens were then used as standards for the determination of comparative specific gravities by the following simple and very accurate method.

About 150 c.c. of a mixture of bromoform and benzene is prepared, of a specific gravity such that the heaviest specimen to be examined just floats in the liquid at room-temperature. The mixture is transferred to a tall narrow-necked bottle of about 200 c.c. capacity, into which a large bulb thermometer, reading to 50° C. in tenths of a degree, is fitted, the bulb being immersed in the liquid. About 50 c.c. of the liquid is then transferred to a boiling tube together with the specimens, and the liquid is boiled for several seconds to expel air. The contents are then returned to the bottle and the temperature at which the various specimens, in rising, pass the half-way suspension point marked on the bottle are read. The bottle and contents are again heated to about 20° C. above room-temperature and the readings repeated. When necessary, the density of the liquid is adjusted by adding a few drops of benzene, or by boiling away a little from the contents of the bottle.

The specific gravity range should be so adjusted that the first specimen rises in the liquid at about 10–15° C. above room-temperature, and the last at about 1° above. Under these conditions, duplicate readings to 0·5° C. are easily obtained and check results usually agree to a fifth or a tenth of a degree. Since each degree rise only represents a decrease in specific gravity of the bromoform-benzene mixture of about 0·002, the method allows of great accuracy for comparative determinations of specific gravity.

A few of the slightly decomposed, non-glassy specimens showed a variation in specific gravity up to 0·01 for different fragments from the same specimen. In these cases a preliminary separation with the bromoform mixture was adopted, and only those specimens having the same specific gravity were taken for the heat-treatment tests.

D. *Correlation of Heat-treatment Results.*

From the foregoing results, it would seem that the change in specific gravity precedes the re-solution of the microperthitic structure on heating. This apparent lack of synchronism could be explained by assuming that the fall in specific gravity is caused by an irreversible change in the crystallographic form of one or the other of the (or, ab) microperthite components, below the temperature of diffusion, the change being truly independent of the re-solution of the microperthite. Since, however, the corresponding orthoclase and albite felspars at the end of the series undergo no such change in volume on heating to temperatures 200° to 300° C. above those at which the changes in specific gravity of the microperthitic specimens are complete, this explanation would imply that the perthite member responsible for the volume-change was in a different condition from ordinary orthoclase or albite, which does not seem probable. Further, if the fall in specific gravity is due to a simple change in form, the transformation ought not to require a temperature range of 200–300° C. for its completion, nor should the end temperatures vary with the proportion of soda-felspar present.

A more reasonable explanation is that the change in specific gravity is due to diffusion, and that the microscopic evidence does not necessarily give a true indication of the amount of re-solution, that is, the lack of synchronism between the two measurements is more apparent than real. It should be pointed out in support of this view that the first effect of diffusion of the (or, ab) lamellae into each other would be to change their composition towards those of the original (Or, Ab) phases without necessarily changing their form. The finer cryptoperthitic (or, ab) lamellae would slowly disappear by diffusion, but this would only make the remaining coarser (or, ab) lamellae appear more prominent under crossed nicols. A much longer time and a relatively high temperature would be required to destroy completely the (or, ab) structures and reproduce the original (Or, Ab) 'shadow' perthite.

According to this interpretation, the reduction in specific gravity would be caused by an increase in volume of one or the other of the (or, ab) components on changing towards the corresponding (Or) or (Ab) phase. Kôzu (18) has suggested that the increase in the linear expansion of certain moonstone felspars between 500° and 800° C. is the result of the dissolving of a solid solution rich in soda-felspar molecules into another rich in potash-felspar molecules. He states that the change is independent of the nature of the soda-felspar. Kôzu evidently here assumes that the transformation is from two solid solutions to a single homogeneous phase. It has been shown in the foregoing pages, however, that for most of the moonstones examined, the two (or, ab) microperthitic structures do not merge by diffusion into one single homogeneous phase, but into two other solid solutions approaching the compositions (Or) and (Ab) respectively. The heterogeneity due to the presence of these two phases is visible under the microscope after the greater part of the change in extinction-angle has taken place, and long after the completion of the specific gravity change. Even in those moonstones which are so low in soda as to yield a single (Or) phase on heating above 700° C., that is, those with less than 25 % soda-felspar, the (ab) member could be assumed, by analogy, to pass through a transitory (Ab) phase, since re-solution, of this nature, is probably a mutual phenomenon.

The changes in specific gravity and extinction-angle which accompany these transformations of (or, ab) into (Or, Ab) are such as to bring the values nearer to those of orthoclase, and farther from those of albite, and the extent of the change is approximately proportional to the amount of soda-perthite (ab) present. Thus it would seem that the transformation of the albite member from (ab) into (Ab) is more responsible for the change in extinction-angle and volume than the transformation of (or) into (Or).

The two higher-temperature phases (Or) and (Ab)—stable above 700° C.—appear to be capable of mutual solution in each other up to the points of saturation indicated on p. 347 without any further marked change in specific gravity and extinction-angle.

The change from (ab) to (Ab) appears to be distinct from Merwin's transformation of albite (β) to barbierite (α) referred to on p. 347. According to Merwin, the β to α transformation does not take place below 900° C. and is very sluggish even at 1000–1100° C., whereas the (ab) to (Ab) transformation, as measured by the specific gravity change observed by me, is completed below 900° C. It may be, of course, that the diffusion of the potash member into the soda member, which takes place during the perthite transformation, profoundly lowers the β- to α-transformation temperature, and that the change from (ab) to (Ab) is simply a modified form of Merwin's β- to α-transformation. With the data at present available, this question must be left open.

Reversal of (*Or*, *Ab*) *Structures.*—The apparent difficulty in destroying the 'shadow' perthite structure by heat-treatment may be due to a partial reversal to these phases from a single solid phase on cooling from 1050–1100° to below 900° C. The form of Laue spot diagram for heated Ceylon moonstone (p. 320) suggests such a reversal of solid solutions down to 700° C.

The behaviour of Korean moonstone examined by Kôzu, which gives a single irreversible Laue spot diagram above 700° C., indicates that this felspar consists of a single homogeneous (Or) phase above that temperature. The Burma Blue specimens which I examined also lose their schiller at about 700° C. They show no signs of (Or, Ab) structures, and their composition also suggests that the (or, ab) structures have separated from a single (Or) phase. One would expect these specimens to give a single Laue spot diagram above 700° C.

Cooling Changes.—It has already been stated that the heat-treatment changes of these felspars are only 'irreversible' during laboratory times. The fact that the microperthitic structures now exist in moonstone shows that the changes would not be irreversible in geological cooling periods. The incomplete exsolution of the Sparling Gulch microperthite proves, however, that the separation must have been slow even in terms of geological time.

Notwithstanding this slowness of separation, it seems probable that the temperatures of transformation, that is, the temperatures at which the phases become stable or unstable, would not differ greatly for heating or for cooling. Thus the temperature of 700° C. might reasonably be taken as the point at which the (Ab) phases on cooling tend to become unstable and the (or, ab) phases to separate. Similarly, the minor change in expansion at 950° C. observed by Kôzu (p. 320) might be taken to indicate the temperature at which a single homogeneous phase begins to separate into the two (Or, Ab) phases. The probable sequence of cooling-changes in these moonstone felspars might therefore be outlined as follows:[1]

(*a*) The potash-soda-felspar would separate from the liquid magma as homogeneous crystals according to the Vogt-Warren equilibrium diagram, at a temperature of about 1150°–1200° C.

(*b*) These crystals on cooling to about 950° C. would separate into two (Or, Ab) phases partly along the common prism-planes (110) and (320) and partly on (100). The separation would be greatest in felspar with 40–45 % of soda-component and under conditions of slow cooling. It might be absent altogether from felspars with less than 20 % (or more than 70 %) of the soda-component, or in felspars quickly cooled, or containing some retarding component.

(*c*) No further important change would take place until the temperature had fallen below 700° C., when the (or, ab) microperthite lamellae would separate along the perthite plane either from the two (Or, Ab) phases or from a single phase if no previous separation of (Or, Ab) perthite had occurred. If the original felspar contained less than 10 % of soda-component, the separation of (or, ab) structures would be impossible. Nearness to this composition would also tend to prevent exsolution of the (or, ab) microperthite; rapid cooling would have the same effect.

(*d*) It is doubtful whether exsolution could continue to take place below a temperature of 350° to 400° C.

Microcline Separation.—The frequent occurrence of the microcline form of potash-felspar in metamorphic rocks has led to the belief that pressure metamorphism has been instrumental in causing the transformation. Alling (1, p. 359) has said that even the pressure imposed during the grinding of sections may result in a partial change of 'orthoclase' to microcline. No such change has been observed, however, in the various moonstone sections examined by the writer.

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[1] In these and previous considerations of phase-changes on cooling the effect of pressure on the change-temperatures has been ignored. Since there is a reduction in volume on exsolution, it is possible that high pressures would raise the exsolution temperatures slightly. For the same reason the melting-points should be similarly increased by pressure so that the relative differences would probably remain much the same as at ordinary pressures.

The occurrence of microcline in such rocks as the Ambalangoda pegmatite, in which there is little or no evidence of metamorphism, indicates that the microcline form of potash-felspar may separate as a normal phase during rock cooling. The chemical and physical conditions which determine the separation of one form or the other of potash- or potash-soda-felspar are not at present understood, but in the case of the Ambalangoda microcline, the change probably took place above a temperature of 700° C., from a single homogeneous potash-soda-felspar phase, and was accompanied by the complete exsolution of the albite component in the form of (ab) lamellae which separated mainly along the perthite plane, but also in part along the junctions of the albite twin lamellae.

Solidus Part of Equilibrium Diagram.—The foregoing results indicate the existence of high-temperature mixed solid-solution phases in the potash-soda-felspar series, for which the Vogt-Warren diagram makes no provision. The speculative diagram of Alling (2) postulates the existence of high-temperature mixed solid-solution phases with a eutectoid containing about 60 % soda-felspar. According to this diagram, a microperthitic felspar with 50–60 % of soda-component would, on heating, become one solid homogeneous phase at a lower temperature than one with about 20 to 30 %, whereas the reverse appears to be the case in the schillerized felspars examined by me. It is evident that much more experimental work on these schillerized felspars will be necessary before the transition lines of the solid phases can be located with any degree of certainty.

10. Selective Decomposition.

After various unsuccessful attempts to decompose these schillerized felspars selectively by the ordinary laboratory methods, I decided to try the effect of steam and carbon dioxide in a closed vessel under high pressure. For these tests a steel bomb was used, similar to that described by G. W. Morey (22). A small gas muffle was adapted for heating the bomb in place of the electric furnace described by Morey. The bomb was found to be gas-tight up to temperatures of 550–600° C.; but it was necessary to quench the bomb straight from the furnace in cases where the liquid contents were to be examined, otherwise the shrinkage due to slow cooling in the furnace allows all except the solid contents to escape in the gaseous state.

In most of the experiments the specimens, together with the reagents, were placed directly in the 80 c.c. of heating-space within the bomb and in direct contact with the steel walls of the vessel. In the few cases where it was desired to prevent contamination with iron compounds the specimen and reagents were placed in a platinum vessel with a loosely fitting lid within the bomb. The carbon dioxide was introduced into the bomb by the simple expedient of adding calculated amounts of oxalic acid and hydrogen peroxide. By this method 1 gm. of carbon dioxide (about 500 c.c. at N.T.P.) can be added for each 13 c.c. of space occupied by the hydrogen peroxide. Since these reagents act on each other slowly at room-temperatures, the hydrogen peroxide was introduced just prior to closing the bomb. In most cases 3 to 4 gm. of carbon dioxide were added. The calculated approximate pressures within the bomb are about 1,500 lb. per square inch at 300° C. and about 6,000 lb. per square inch at 450° C. respectively.

The felspar fragments for these bomb-tests were carefully selected with clean, sharp, cleavage faces parallel to (001) and (010), so that any etching effect could be readily observed. They included specimens from Ceylon and Burma, the two albite specimens mentioned, and microcline.

The following is a summary of the results obtained:

(*A*) All the schillerized moonstone felspars were slowly attacked (and more or less selectively) by steam and carbon dioxide at temperatures above 300° C., the action being much more rapid at 500° C. than at 300° C.

(*B*) The coarsely-microperthitic white stones were more strongly attacked than the blue-white and blue stones, the white specimens becoming deeply etched and opaque in a few hours at the lower temperatures, while the Burma blue stones required, in some cases, two or three days at this temperature for the same depth of etching.

(*C*) The decomposition takes place along two different directions or sets of planes in the felspar and is of two different types.

(*a*) The first action, which does not appear to be selective, is an attack on the felspar along the traces of the prism-plane (110), the basal cleavage surface being etched with clear sharp rhombs. When lightly etched, the rhomboidal patterns are shallow depressions, with the long axis parallel to the trace of (100). The acute angle between the prism lines is about 60°. If more deeply etched, the depressions become pyramidal recesses with two minute prism-faces sloping forward into the recess from the two back edges of the rhomb, the front obtuse angle becoming rounded. If the face is very strongly etched, the rhombs may join up into a lattice pattern. The cleavage face (010) is etched into sharp straight lines or furrows parallel to the crystallographic axis *c*.

The non-schillerized Burma 'Colourless' stone shows this type of decomposition best, but, by making the action less selective, this form of etching can be made to predominate in some of the blue moonstones. Pl. XV, figs. 15 and 16 show the effect of this type of etching on the (001) cleavage surface of Burma 'Colourless' and Burma Blue II specimens respectively.

(*b*) The second type of decomposition is by attack of the (or, ab) microperthitic structure of the schillerized felspars selectively, the (ab) component being attacked more than the (or), with the result that the microperthitic structure is rendered clearly visible on the cleavage faces even in the case of those blue moonstones in which the (or, ab) structures are invisible, or only partly visible, by the microscopic methods previously described. For the same set of conditions, this type of decomposition affects the white specimens more than the blue. In all the bomb-tests, and with all the varied conditions of experiment, the Burma 'Colourless' and the albite specimens showed immunity to this type of decomposition.

The selectivity of this type of attack was proved by a bomb-test with 50 c.c. of distilled water and 3½ gm. of carbon dioxide on 1 gm. of powdered Ceylon moonstone containing 3·8 % of soda and 10·5 % of potash. After the test the liquid was found to contain 0·05 gm. of mineral matter in solution, of which 0·011 gm. was sodium oxide and 0·014 gm. was potassium oxide. Thus the soda is being removed at nearly the same rate as the potash from a felspar containing nearly three times as much potash as soda. The quantities of material recorded above in solution, although probably not a maximum for the conditions of the test, indicate a high order of mineral solubility. Expressed in parts per 100,000 the quantities are: total solids 100, sodium oxide 22, potassium oxide 28.

We may compare these figures with those of the solubility of limestone in water saturated with carbon dioxide, which is regarded as a powerful natural solvent for the rock. The maximum solubility of $CaCO_3$ in this solvent at 10° C. is $CaCO_3$ 88 parts, or as CaO 50 parts, per 100,000. The two sets of solubility figures are of the same order.

(*D*) An examination of the blue schillerized moonstones shows a gradation between the two above-mentioned types of decomposition as the soda-content increases. Thus, with the Burma Blue I specimen, the etchings on (001) are not unlike those of Burma 'Colourless' except that the rhombs tend to be longer and the obtuse angles of the pattern more rounded (pl. XV, fig. 16). On the (010) face the prominent lines parallel to the *c*-axis are supplemented by very fine microperthitic lines parallel to the trace of *Δ*. With increasing soda-content and coarser microperthitic structure, the rhomboidal etchings on (001) become more and more elongated and elliptical, and fine short lines parallel to the trace of (100) appear. Similarly, on (010), the fine microperthitic lines become more and more prominent and the lines parallel to the *c*-axis become less evident.

(*E*) Water and steam alone attack moonstones under pressures corresponding to 400–450° C. The action is rather that of a general solvent, being less selective than water and carbon dioxide together. The tendency, with water alone, is to develop the (Or, Ab) structures more than the fine (or, ab) microperthite.

(*F*) The selectivity of the attack on the microperthitic structure can be markedly increased by adding potash salts to the solution, but the reaction is then complicated by the deposition of small crystals of an alkali alumino-silicate mineral on the moonstone cleavage faces. These crystals are biaxial and have the form of hexagonal or rectangular tablets. They sit, limpet-like, in corroded depressions on the cleavage surfaces of the felspar. The decomposition of the felspar has evidently proceeded with greater rapidity in the vicinity of these tabular crystals. The effect of this type of attack on Ceylon blue moonstone, together with the appearance of the deposited crystals, is shown on pl. XV, figs. 17 and 18.

(*G*) The character of the etching is affected by the heat-treatment previously described. A specimen of Burma Blue II heated for some time at 1050° C., when subsequently etched in the bomb, yielded only the rhomboidal pattern type of attack (similar to Burma 'Colourless'), whereas an ordinary specimen of the same moonstone etched at the same time gave elongated ellipses on (001), with fine sharp microperthitic lines on (001) and (010).

(*H*) The difference in internal structure between moonstone felspar and microcline-microperthite is illustrated by the bomb etching-tests. The lines of etching on basal cleavage surfaces of the microcline follow the (ab) lamellae along two perpendicular directions parallel to the trace of (100) and (010) respectively, that is, parallel to the lines of microcline twinning. The etchings are unmistakably different from the rhomboidal pattern of Burma 'Colourless', or the modified ellipses of the microperthitic moonstones.

(*I*) The solvent action of water, steam, and carbon dioxide on some minerals is considerable, even at relatively low temperatures and pressures. Thus a specimen of opal, $\frac{3}{8}$ inch in diameter, was dissolved to a friable skeleton by heating to 300° C. for a day with water and carbon dioxide. Moonstone is practically unacted on at this temperature and pressure. Quartz and fluorite crystals are strongly attacked on heating for 40 hours at 400–450° C.; the edges of the quartz crystals being rounded and the faces deeply corroded with parallel furrows and geometrical patterns, similar to naturally-etched crystals.

Selectivity and De-albitization.

The data obtained from these high-pressure solution tests throw light on the conditions which probably obtained during the decomposition of the Ambalangoda pegmatite. It has already been pointed out on p. 315 that the presence of graphite in this pegmatite, and the occurrence of graphite, calcite, scapolite, and sphene in adjacent pegmatites of this area, indicate that carbon dioxide and other pneumatolytic gases have acted upon the pegmatites in the later stages of cooling of the rocks, that is, during the stages of pneumatolysis and hydatogenesis.

Pressures equivalent to those of the bomb-tests would not require greater depths for their attainment than one-half to one mile. With these pressures and the presence of carbon dioxide and possibly other volatile substances in the water and steam escaping from below, the decomposition of the pegmatite along the walls of the fissures and cracks would be rapid. If these solutions, ascending under pressure, possessed the same solubility ratio for soda and potash as was found in the bomb-tests, the excess of potash over soda in the pegmatite would saturate them with potash before they became saturated in respect to soda. The action would then be more selective on the soda-felspar, and de-albitization of the microperthite would follow.

The ultimate fate of all the pegmatite subjected to prolonged action of the ascending solutions would be complete decomposition and kaolinization of the felspar, removal of the silica and decomposition of the ferromagnesian minerals. Only in the regions of partly decomposed rock would the de-albitized felspar ultimately be found, sometimes with hard cores, and generally associated with the more potassic undecomposed moonstones, just as in the Ambalangoda pegmatite residues.

11. Summary and Conclusions.

1. Moonstone felspar from a rotted pegmatite intrusion near Ambalangoda, in south-western Ceylon, has been found to possess a microperthitic to sub-microperthitic structure. The microperthitic lamellae (or, ab) have separated mainly along the plane $\varDelta$ (13.0.$\bar{2}$), which is also the plane of schiller. In addition to the fine microperthite, a coarse but fainter (Or, Ab) 'shadow' perthite occurs in the moonstone. This structure separated earlier than the fine microperthite, mainly along the prism-planes (110) and (320).

2. Semi-decomposed specimens from the same pegmatite residue were found to consist of de-albitized microperthite. The removal of the albite lamellae has shown up the two types of perthitic structure plainly under the microscope, and the (or, ab) structures to a very fine degree of subdivision.

3. Schillerized felspars from Kandy, Burma, and Colorado have been examined and found to possess microperthitic structures similar to the Ambalangoda moonstones. In all these specimens the schiller colour is dependent on the size and relative abundance of the microperthite lamellae. The schiller is mainly due to reflection and scattering of light at the boundaries of these lamellae. Specimens with zoned schiller possess corresponding differences in microperthitic structure in different zones.

4. The specific gravity, optic axial angle, and extinction-angle of these schillerized felspars are dependent on the proportions of the two felspars present. Where the separation of the microperthitic structure is complete the specific gravity and extinction-angle are near the calculated means for the proportions of orthoclase and albite present, that is, the relationship is a straight line. For the optic axial angle and composition the relationship is a curve slightly concave towards the composition axis. In the case of incomplete exsolution, as with specimens from rocks that have been quickly cooled, the specific gravity, extinction-angle, and optic axial angle all show a departure from the normal towards the potash-felspar side, and the schiller colour and intensity are also abnormal for the soda-content.

5. The schiller colour and microperthitic structure of these felspars

can be destroyed by heat-treatment. At the same time the specific gravity, optic axial angle, and extinction-angle are reduced. The reduction in the extinction-angle and specific gravity is—for the specimens examined and containing up to 40 % of soda-component—roughly proportional to the amount of microperthitic albite originally present, being least in the non-schillerized end-members of the series. The reduction in the optic axial angle, on the other hand, is least in the highly perthitic felspars and greatest in the low-soda orthoclase with no schiller or perthitic structure. The changes in schiller, specific gravity, and extinction-angle appear to be due to a re-solution of the (or, ab) members of the microperthite into each other to re-form the original (Or, Ab) phases. This transformation of (or, ab) to (Or, Ab) appears to have very little effect on the optic axial angle.

6. The microperthite can be attacked selectively by heating with water and carbon dioxide under pressure. In this way, the (or, ab) structures can be 'developed' on the cleavage faces so that they become readily visible under the microscope, even in those blue moonstones which show little or no evidence of microperthite by ordinary microscope methods. This selective decomposition gives a clue to the manner in which the de-albitization of the Ambalangoda specimens may have been brought about.

7. The various phenomena associated with the heat-treatment of these felspars indicate that the equilibrium lines of the solidus part of the Vogt-Warren thermo-equilibrium diagram are not adequate to explain the changes which occur. The curves on Alling's recent speculative diagram, while providing for the existence of high-temperature mixed solid-solution phases, do not appear to be quite in accord with my heat-treatment observations on these schillerized felspars. There appear to be two solid-solution changes: (*a*) at about 900–1000° C. between a single solid-solution phase and the two (Or, Ab) phases; and (*b*) at about 500–700° C. for the (or, ab) separation, either from the two (Or, Ab) phases or from one of them. These two solid-solution changes can be brought about by heating in the laboratory, but the reverse exsolution changes apparently cannot be accomplished in laboratory times.

8. Microcline may not always be a product of pressure metamorphism. In Ambalangoda microcline-microperthite the (ab) lamellae have separated along the planes of twin-composition and the conversion to microcline has evidently taken place prior to the exsolution of the microperthite, and hence probably above 700° C. The

composition, extinction-angle, and specific gravity of this microcline do not conform to the relationships found for moonstone felspar and the specimen shows none of the corresponding changes on heating and no re-solution of the microperthite. Microcline appears to be the stable form of potash-felspar and to be incapable of holding albite in solid solution up to temperatures near the fusion point of the felspar.

I should like to express my indebtedness to Prof. P. G. H. Boswell for his kind help and suggestions throughout the work and for facilities provided in the Geological Laboratories of the University of Liverpool for analytical and optical work. I wish also to thank Messrs. Bird & Co., of Calcutta, for permitting the work to be completed in their Research Laboratories, and Mr. K. B. Sen, M.Sc., A.I.C., for his help in carrying out analytical checks on all the specimens examined and for his assistance in the determination of specific gravities, heat-treatment changes, &c. Further, I am indebted to the Geological Survey of India for kindly supplying me with specimens of albite from Amelia, yellow orthoclase from Madagascar, and adularia from St. Gotthard.

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EXPLANATION OF FIGURES ON PLATES XIII–XV.

The reader is recommended to examine the photographs showing microperthitic structures with the aid of a pocket-lens, in order to observe the extremely fine laminae, *many* of which, even at this magnification, are too fine to be seen by the naked eye. Figs. 1–11, specimens from Ambalangoda, Ceylon.

FIG. 1. Cleavage-flake on (010) of a white moonstone (from specimen A, pp. 300, 307 in ordinary light seen from the positive direction of the *b*-axis; *c*-axis approximately vertical. × 185.

FIG. 2. Same specimen as fig. 1, under crossed nicols and near the extinction position; *c*-axis approximately vertical. × 185.

FIG. 3. From the same specimen as figs. 1 and 2, cleaved on (001), under crossed nicols and near extinction position; *b*-axis approximately horizontal. × 185.

FIG. 4. Cleavage-flake on (010) of blue-white moonstone (specimen C, p. 302) seen from the negative direction of the *b*-axis, under crossed nicols and near extinction position; *c*-axis approximately vertical. × 185.

FIG. 5. Cleavage-flake on (010) of fresh portion of a de-albitized moonstone showing large thin albite lamellae. Seen from the positive direction of the *b*-axis, under crossed nicols. Groundmass near extinction position; *c*-axis approximately vertical. × 185.

FIG. 6. De-albitized moonstone boiled in methylene blue and cut parallel to (010). Seen from the negative direction of the *b*-axis in ordinary light; *c*-axis approximately vertical. × 200.

FIG. 7. De-albitized moonstone dyed and cut parallel to (001); *b*-axis approximately horizontal. × 200.

FIG. 8. Cleavage-flake on (010) of a white moonstone (specimen A, pp. 300, 318) heated to 1050° C. for 12 hours. Under crossed nicols, near extinction position; *c*-axis approximately vertical. × 185.

FIG. 9. Cleavage-flake on (001) of white stone (A, pp. 300, 318) heated to 1050° C. for 12 hours. Under crossed nicols near extinction position; *b*-axis approximately horizontal. × 185.

FIG. 10. Section of microcline-microperthite-pegmatite from exposure Y (fig. 1, and p. 327). Under crossed nicols. × 9.

FIG. 11. Section of a microcline-microperthite crystal from the above pegmatite to illustrate the relatively coarse, regular microperthite. Right half shows a flake ground on (010) seen in ordinary light; *c*-axis approximately vertical. Left half shows a flake ground on (001) under crossed nicols with microcline twin-lamellae in 'neutral' position to show up the short pegs of albite; *b*-axis approximately horizontal. × 185.

FIG. 12. Cleavage-flake on (010) of white moonstone from Mogok, Burma (p. 332). Seen from the negative direction of the *b*-axis, under crossed nicols and near extinction position; *c*-axis approximately vertical. × 200.

FIG. 13. Schillerized 'sanidine' from Ragged Mountain, Colorado (p. 333). Baveno twin, cut parallel to (100) and polished. Seen by reflected light with spot-light illumination for each twin half at a suitable angle to give uniform schiller intensity. The photograph shows schiller zoning in the crystal. *c*-axis vertical. × 2.

FIG. 14. Section of Ragged Mountain '*sanidine*' (p. 334) crystal cut parallel to (010). Seen from the positive direction of the *b*-axis, under crossod nicols

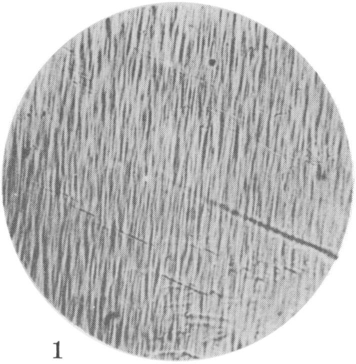
and near extinction position; *c*-axis approximately vertical. Shows coarse (or, ab) microperthite in the white zone and fine (or, ab) microperthite in the blue zone, with an abrupt change at the junction of the zones. Traces of basal cleavage seen as dark lines near the top of the photograph. × 140.

FIG. 15. Burma 'Colourless' stone (p. 359). Cleaved rhomb etched for 24 hours at 400° C., under pressure with water and carbon dioxide. Cleavage-flake (001) seen from the positive direction of the *c*-axis, by transmitted light; *b*-axis horizontal. Shows a characteristic rhomboidal pattern seen on all etched (001) surfaces of orthoclase low in soda. × 90.

FIG. 16. Burma Blue II specimen (p. 359). Cleaved rhomb etched for 24 hours at 400° C., under pressure with water and carbon dioxide. Cleavage-flake (001) seen by reflected light; *b*-axis horizontal. Note how the etchings have been modified from the sharp rhombs seen in fig. 15 to elliptical lenses, owing to the effect of the fine microperthitic structure. × 90.

FIG. 17. Ambalangoda Blue moonstone (p. 360). Cleaved rhomb etched for 40 hours at 400° C., under pressure with water, carbon dioxide, and a small quantity of potassium carbonate. Cleavage-flake (010) seen by transmitted light; *c*-axis approximately vertical. Shows (Or, Ab) structure prominently and (or, ab) structure faintly. The hexagonal crystal seen at the bottom of the photograph is an alkali alumino-silicate produced during the etching test. The crystal lies in a corroded depression on the etched surface of the felspar. × 90.

FIG. 18. Cleaved flake from the (001) surface of the same specimen as fig. 17 seen by transmitted light; *b*-axis horizontal. Shows elongated rhombs and lenses and very fine short microperthite lamellae. Also three tabular crystals of the alkali alumino-silicate. × 90.



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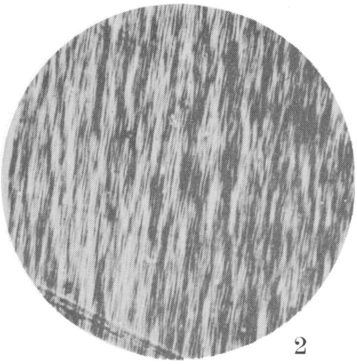

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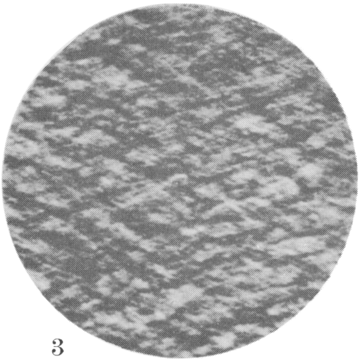

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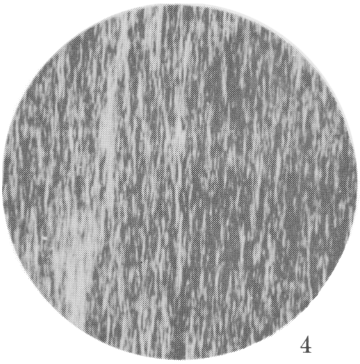

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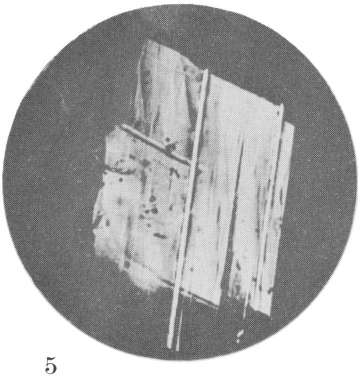

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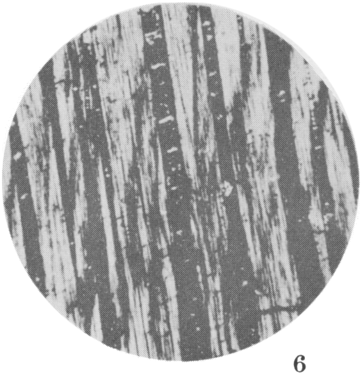

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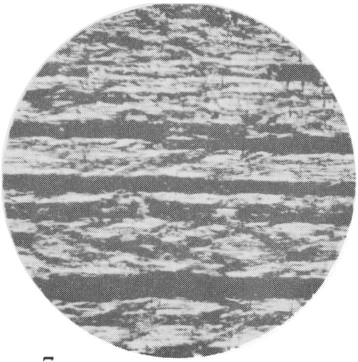
E. SPENCER: MOONSTONE FROM CEYLON.



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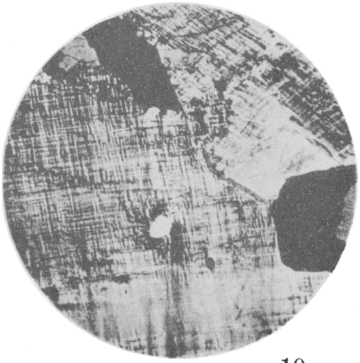

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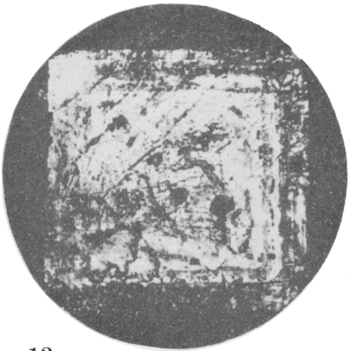
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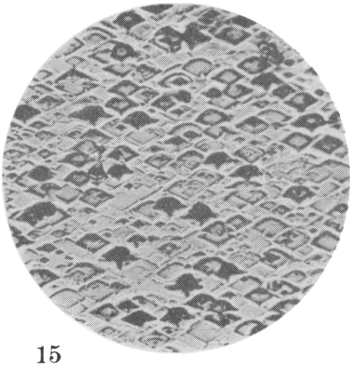
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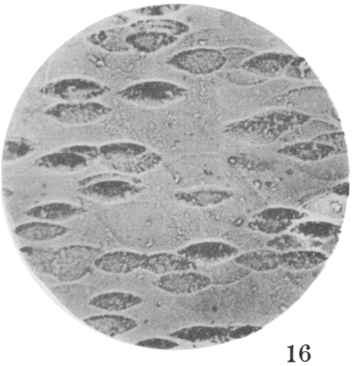
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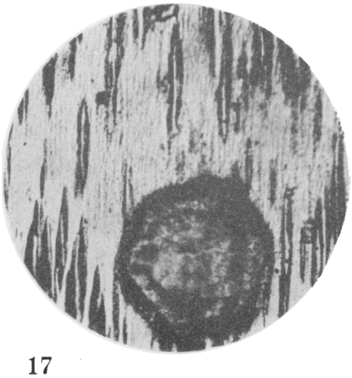
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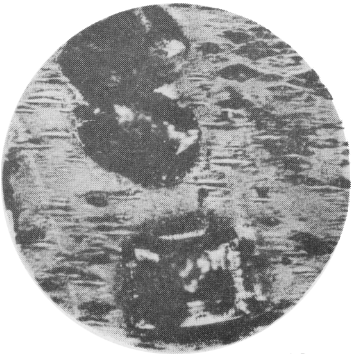
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E. SPENCER: MOONSTONE FROM CEYLON, &c.