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The potash-soda-felspars.

II. Some applications to petrogenesis.

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CONTENTS.

	PAGE		PAGE
I. The origin of the microcline of pegmatites . . .	87	(f) Immiscible potash- and soda-rich magmas . . .	101
II. The temperatures of crystallization of the potash-soda-felspars . . .	90	(g) Diagram illustrating liquid immiscibility . . .	103
III. The alkali-felspar equilibrium diagram . . .	92	IV. Quartz-microcline graphic structures . . .	105
(a) The exsolution curve . . .	94	V. The origin of 'vein' perthite . . .	106
(b) The solidus-liquidus curve . . .	95	VI. Effects of pressure on the exsolution curve . . .	108
(c) Application of the thermal diagram to granite magmas . . .	97	VII. High-temperature pegmatites . . .	110
(d) The composition of granite-pegmatites . . .	99	VIII. Syngenetic felspars formed by solid diffusion . . .	111
(e) Cause of the potassic enrichment of granite-pegmatites . . .	100	IX. Summary . . .	114
		X. List of works to which reference is made . . .	116

IN the first part of this paper (33) the effects of heat on the potash-soda-felspars were considered, and a possible explanation in terms of atomic rearrangement was proposed. In this part the experiments, and deductions from them, will be applied to some questions of petrogenesis and differentiation, particularly in connexion with the granites and granite-pegmatites.

I. THE ORIGIN OF THE MICROCLINE OF PEGMATITES.

In the high-temperature pegmatites, such as those of Fredriksvärn and the moonstone-pegmatites of Ceylon and Burma, the potash-soda-

felspar occurs as anorthoclase or microperthitic orthoclase.¹ In the granites, crystallized probably between 750° and 950° C., this felspar occurs sometimes as microperthitic orthoclase and sometimes as microcline, but in the granite-pegmatites, formed within the temperature range of 500° to 750° C., it appears almost invariably as microcline. In the hydrothermal temperature region below 400° C. only adularia is produced.

Why should crystallization in the 500° to 750° C. temperature region favour the formation of the triclinic form? Warren (41, p. 148), who observed the persistence of microcline and the absence of orthoclase in the granite-pegmatites, introduced an 'inversion' point into the equilibrium diagram to account for the change in form from orthoclase to microcline. According to his interpretation the inversion is probably accompanied by a reduction in solubility for the albite-component, with intensified perthitic exsolution. The inversion makes no provision for the lower-temperature, monoclinic adularia.

The suggestion of Mallard (26) and Michel-Lévy (27) that orthoclase may be a pseudo-monoclinic, sub-microscopically twinned form of microcline avoids the necessity for inversion points. The production of the ordinary coarsely twinned microcline form instead of the pseudo-monoclinic 'orthoclase' form in granite-pegmatites could then be explained by molecular disturbance set up during simultaneous crystallization and exsolution. Against this view of pseudo-monoclinic symmetry are a number of facts already brought out in the first part of this paper, which may be summarized as follows:

1. The orthoclase-microperthite felspars provide an unbroken series which by heat-treatment can be converted into corresponding members of the sanidine-anorthoclase series. The assumption of a sub-microscopic twin-structure for any of these felspars would have to apply to all of them. It is highly unlikely that sanidine, with its optic axial plane parallel to (010), is sub-microscopically twinned, and therefore it is equally improbable that any are.

2. The optic axial angle of orthoclase-microperthite increases with increasing soda-content and lower equilibrium temperatures. The lowest-temperature orthoclases have a smaller optic axial angle than microclines of corresponding composition. This difference cannot be

¹ A number of these soda-rich felspars (Fredriksvärn soda-orthoclase, Berkum anorthoclase, &c.) have sometimes been referred to microcline, but specimens of them which I have examined do not show microcline twinning, but a 'cross-hatching' due to microperthite.

due to relative coarseness of lamellar twinning in the microcline, since the optic axial angle of the latter is already 'averaged' over a large number of microscopic twin-lamellae, and any further subdivision would not alter this average value appreciably.

3. The solubility of the soda-component in ordinary microcline is less than in orthoclase. This would not be so if the feldspars differed merely in the fineness of multiple twinning.

4. By prolonged heating, microcline can be converted to the sanidine form. This change is much more difficult to bring about than in members of the orthoclase-micropertthite series of corresponding composition.

These observations indicate a fundamental difference between orthoclase and microcline, and support Warren's hypothesis of inversion, rather than the hypothesis of pseudo-monoclinic symmetry in orthoclase.

In the light of experiments described in the first part of the paper, and of recent interpretations of feldspar structure, the formation, in some cases of orthoclase, in others of microcline, might be explained as follows. High-temperature crystallization and rapid cooling produce sanidine and anorthoclase forms, monoclinic or almost monoclinic in character even when containing some 50 % of soda-component. In these the sodium-ion fulfils essentially the same function as the potassium-ion in the tetrahedral structure. Of the three principal properties which distinguish albite from orthoclase, viz. refractive index, oblateness of indicatrix, and triclinic symmetry, only the refractive indices are altered slightly towards albite by the inclusion of 50 % of sodium-ions in the anorthoclase structure at high temperatures.

At temperatures of formation down to 850° C. the feldspar is still monoclinic and homogeneous (with up to 30 % of soda-component), but the oblateness of the indicatrix and the optic axial angle have increased considerably. This is due in part to the sodium, and in part to the potassium-ion. It may be assumed that this increase in oblateness, which is accompanied by a decrease in the mutual solid solubility of the two feldspars, represents a tendency toward a true triclinic symmetry of the soda- and (by analogy) of the potash-component.

In the feldspars formed near 850° C., the sodium-ions produce the same oblateness of indicatrix in the homogeneous feldspar as they do when separated at lower temperatures in perthite lamellae. On exsolution, the density and refractive index of the soda-feldspar lamellae increase to the albite figure, but true triclinic symmetry is apparently not

attained.¹ It seems that soda-felspar of exsolution origin can only take on true albite symmetry when the potash-felspar host at the same time takes on triclinic microcline symmetry. This appears to be possible only when the oblateness of the indicatrix of the potash-felspar is at, or near, a maximum.

When, as in the granite-pegmatites, crystallization falls within the exsolution temperature range of 450° to 750° C., the oblateness of the indicatrix of the potash-felspar is probably near the maximum. Under these conditions albite and potash-soda-felspar are often separating simultaneously from the same magma, while exsolution takes place in the potash-soda member on a slight fall in temperature. This, in the writer's view, represents the optimum condition for the formation of the microcline form.

For still lower crystallization temperatures in the hydrothermal region, the oblateness of the indicatrix would be such that microcline might form, but the necessary disturbing conditions would not usually be present, with the result that the monoclinic form *adularia* is commonly produced. Alling (1, p. 267) has suggested that the process of grinding sections might cause the inversion of *adularia* to microcline. The behaviour of *adularia* toward heat-treatment places it nearer to the microclines than to the orthoclase-micropertthite series.

II. THE TEMPERATURES OF CRYSTALLIZATION OF THE POTASH-SODA-FELSPARS.

If we assume that the micropertthitic feldspars were originally homogeneous and that they held the maximum amount of soda-component in solution at their crystallizing point, the temperature at which they now become homogeneous is probably that at which they were formed, if the effects of pressure can be neglected (see later). In the case of soda-poor feldspars formed in potash-rich magmas, the temperature of formation may be somewhat higher than that at which the perthite is redissolved.

The probable crystallizing temperatures of various potash-soda-

¹ The perthite films show no signs of lamellar twinning, while sections on (001) of the felspar, as a whole, show straight extinction. Sections on (001) show a symmetrical interference-figure. It may be that these lamellae represent the monoclinic form of soda-felspar (*barbierite*). If so, this form is more common than has generally been supposed. Barth (6) has described an antiperthite from Seiland the soda-felspar groundmass of which is uniform and shows straight extinction on (001); but certain parts of the same crystal show slightly oblique extinction and evidence of sub-microscopic lamellar twinning.

felspars are set out in the table below. For completeness, soda-rich representatives are included although knowledge of their temperature of formation is less certain.

Temperatures of formation.	High potash.	High soda.
1100° to 950° C.	40 to 60 % soda-felspar. On slow cooling from high temperatures—schillerized felspar of Burma moonstone type. Sanidine and anorthoclase when more quickly cooled.	Over 70 % soda-felspar. (Usually with some lime.) Oligoclase when slowly cooled. Soda-anorthoclase when rapidly cooled.
950° to 750° C.	25 to 40 % soda-felspar. The common micropertithic orthoclase with high optic axial angle and schiller.	Over 80 % soda-felspar. Some albite-oligoclase.
750° to 400° C.	10 to 25 % soda-felspar. Mainly microclines, with some medium-soda, high-optic axial angle moonstone - orthoclase - micropertithes.	Over 85 % soda-felspar. Pegmatitic albite-oligoclase.
400° C. and below	0 to 15 % soda-felspar. Adularia.	Over 90 % soda-felspar. Hydrothermal albite (cleavelandite).

Some true orthoclases, lower in soda than microcline or adularias, e.g. yellow orthoclase and Burma colourless of the first part of this paper, have probably been formed at relatively high temperatures and possibly high pressures, from magmas very poor in soda.

From field and petrological evidence Vogt (37, pp. 64-68) deduced the crystallizing temperatures of various potash-soda felspars to be as follows:

Temperature.	Percentage of soda-component:	
	Orthoclase type.	Albite type.
About 1000-1050° C.	About 60 %	About 68 %
„ 850° C.	„ 32	„ 89
„ 750° C.	„ 27	„ 93
„ 350° C.	„ 14	„ 97
„ 15° C.	„ 9	„ 98

It will be seen that the results of the heat-treatment experiments lead to figures similar to Vogt's and afford an independent check on estimates of the temperatures of formation of rocks containing these felspars.

III. THE ALKALI-FELSPAR EQUILIBRIUM DIAGRAM.

Many attempts have been made to explain the crystallization of the potash-soda-feldspars by means of the binary equilibrium diagram.¹ Vogt (35, p. 485) and Warren (41, p. 148) concluded from a study of granites and granite-pegmatites that the equilibrium diagram was of Roozeboom's type V, with a wide immiscibility gap and a eutectic point at about 60% soda-component. Mäkinen (24, p. 148), from a similar study,

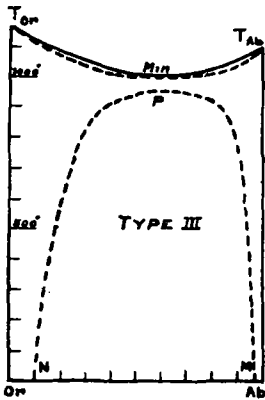


FIG. 1.

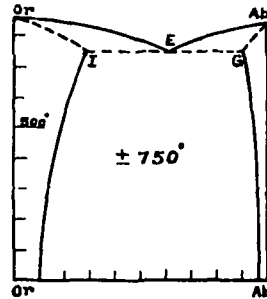


FIG. 2.

Alkali-feldspar equilibrium diagrams.

After J. H. L. Vogt, 1926 (37, pp. 88, 91).

made the immiscibility gap much smaller, and the eutectic at about 70% of soda-component. Dittler (13), from experiments on the melting-points of alkali-feldspar mixtures, decided that orthoclase and albite crystallized according to Roozeboom's type III diagram, with a minimum and no eutectic.

Alling (2, p. 289) suggested that these divergent views might all be more or less true for different conditions of crystallization. He combined the various diagrams into a solid model, with an immiscibility gap that increased towards the low-temperature (pegmatitic feldspar) end. Similarly, Vogt (37, pp. 88-91) has suggested a number of diagrams

¹ In this discussion the incongruous melting of low-soda orthoclase into leucite and silica as described by Morey and Bowen (28) is ignored. Silica in excess sufficient to prevent the formation of leucite is always present in the rocks under review. The more recent ternary diagram of Schairer and Bowen (29), with excess silica as a third component, is referred to later, see page 98.

with increasing immiscibility gaps at progressively lower temperatures. For the highest temperatures, in the absence of fluxes, he takes Dittler's solidus-liquidus curve as most probably correct (fig. 1). For the temperature 750° C., with fluxes and mineralizers present, his diagram has a very wide immiscibility gap (fig. 2).

The effect of fluxes and mineralizers must be to depress the solidus-liquidus curve along its whole length, and not merely in the eutectic

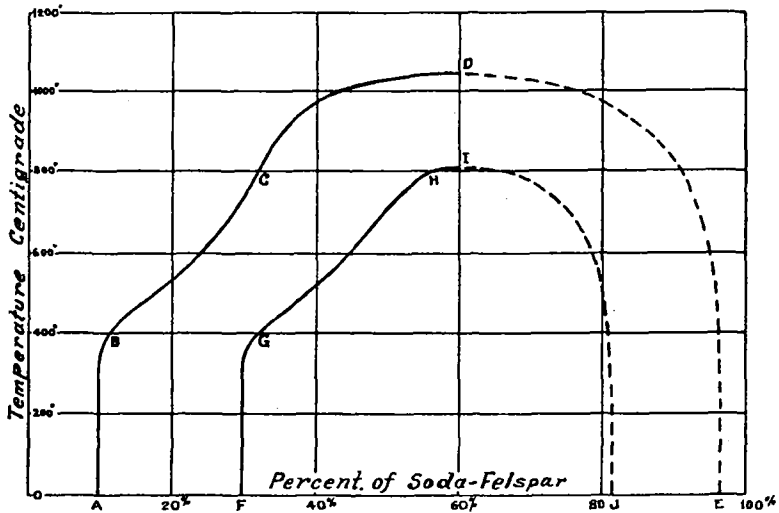


FIG. 3. Exsolution curves for normal and subnormal potash-soda-felspars.

region. This general lowering of the crystallizing temperature is not, of course, unique. A similar effect is produced in the plagioclase-felspars, but here the lowering of the crystallization temperature has no serious effect on the equilibrium diagram, as complete solid solubility of the two components is maintained down to ordinary temperatures. With the alkali-felspars, however, the depression of the solidus-liquidus curves causes them to meet and intersect the exsolution curves at successively lower and lower temperatures, giving rise to an increase in the immiscibility gap, and a corresponding decrease in the amount of solid solution (and ultimately of perthite) in the crystallizing phases.

The factors that affect the solidus-liquidus curve have little direct effect on the exsolution curve, and vice versa. The two parts of the diagram may be considered separately.

(a) The exsolution curve.

From the experiments of Warren and of Kôzu and from a study of the range of composition of alkali-felspars in igneous rocks, Vogt (37, pp. 64–91) deduced that the exsolution curve of fig. 1 is smoothly convex. The experiments described above indicate a relatively sudden change in the solubility of the soda-component in the 350–750° C. temperature range. The curve of fig. 3 (p. 93) shows the flexure due to an increase in the solubility of perthite at 400–500° C., and a decrease at 700–800° C. Heat-treatment experiments have indicated that for temperatures higher than 800° C. and up to the fusion-point of the felspar concerned further solution of perthite takes place at a much slower rate. This is generally accompanied by a reduction in the size of the optic axial angle.

The upper curve of fig. 3 is for normal felspars, formed either by very slow cooling from high temperatures, or by crystallization at lower temperatures with complete equilibrium of optic axial angle and perthite formation. *FGH* represents the exsolution curve for 'subnormal' felspars formed at high temperatures and rapidly cooled (e.g. the Berkum anorthoclase). The incomplete equilibrium caused by rapid cooling¹ is shown in the smaller optic axial angle and reduced oblateness of the indicatrix, while the amount of exsolution is less than in corresponding normal forms. For more rapid cooling, as with some sanidines, and the artificially sanidinized felspars, the optic axial angle is still lower, and exsolution does not take place. It follows that Vogt's diagram (fig. 1), which combines Roozeboom's type III solidus-liquidus curve with the ordinary exsolution curve, can only hold for very high temperatures of crystallization, combined with extreme slowness of cooling.

It was shown above that, by heating perthitic felspars to 800–850° C. and cooling them rapidly, homogeneous metastable forms with 'normal' optic axial angles could be produced, to which the exsolution curve *ABCD* does not apply. Even in volcanic rocks such rapid cooling does not occur. All natural potash-soda-felspar with 'normal' optic axial angles must be completely perthitic to the extent of the exsolution curve *ABCD*.

It follows that, for the potash-soda-felspar series in general, the exsolution curve is not dependent on the cooling rate through the

¹ The term 'rapid' is used here in a relative sense to mean sufficiently rapid to produce felspars with low optic axial angles, and is contrasted with the slower cooling (of deep-seated rocks) which would produce felspars with high optic axial angles.

exsolution temperature range, but on modifications in the atomic structure, which are determined by the cooling rate in the higher temperature regions.

The main difference in the form of the curve *ABCD* from that of Vogt (fig. 2) is the flexure of *ABCD* at 400–800° C. The form of the exsolution curve for 60–100 % soda-component is at present largely conjecture. It has already been suggested (Part I, p. 490) that true potash-soda-felspar representatives in the 60–80 % soda-component region may not exist, but until further information is available one may accept Vogt's continuation of the curve for normal feldspars over this region.

(b) *The solidus-liquidus curve.*

For high-temperature crystallizations, with fluxes and mineralizers scarce or absent, we may take Dittler's curve (fig. 1) as approximately correct. The depression of this curve by fluxes should be more or less uniform over the felspar field. The intersection of the solidus-liquidus curve with the exsolution curve at successively lower temperature levels down to 800° C. is shown in fig. 4 (p. 96). Below 800° C. it is possible that other factors come into play; this part of the diagram will be discussed later in connexion with the potassic enrichment of granite-pegmatites.

If we regard the fluxes and mineralizers (including the water and excess silica) as equivalent to the third component of a ternary mixture, the falling temperature levels of fig. 4 would be produced from successive parallel vertical sections of the solid ternary-component model, starting with pure alkali-feldspars and progressing in the direction of increasing amounts of flux-component as more and more felspar (and silica) are removed by crystallization.

The point *C* of fig. 4 which normally represents the lowest melting-point mixture or eutectic of a binary system, now becomes, on the model, a line along the bottom of a falling valley, for which Vogt (39, p. 411) has suggested the term 'cotectic'. He assumes that the cotectic ratio between the potash- and soda-feldspars remains constant at about 40 : 60 %, as the immiscibility gap increases with decreasing crystallization temperatures and increasing quantities of mineralizers. The accumulated evidence of the alkali-feldspar-bearing rocks tends to support this view, at least down to crystallization temperatures of the order of 800° C.

A peculiarity of the binary cotectic diagram for the alkali-feldspars is that it allows the possibility of changing composition with falling

temperatures, although the cotectic ratio of the magma remains constant. Thus crystallization through the temperature range T_1 to T_2 would produce potash-soda-felspars of gradually changing composition from R to N (about 38 to 32 % of soda-component) together with soda-felspars of S to U composition. Meanwhile the felspar ratio in the remaining magma would be constant at CC_1 , with 60 % of soda-component.

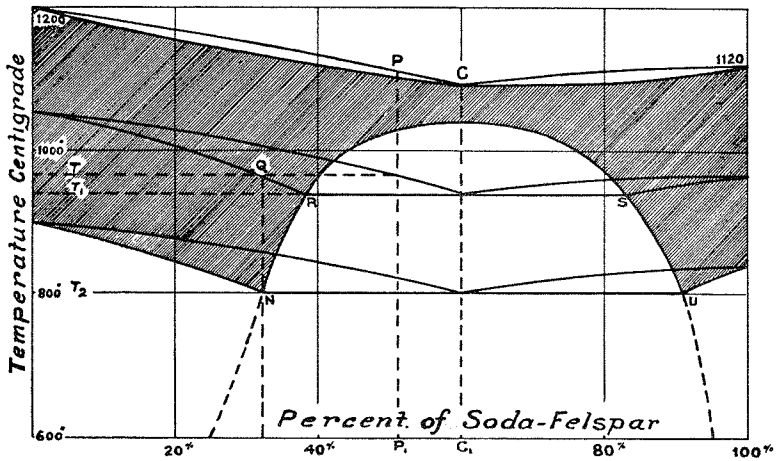


FIG. 4. Suggested cotectic diagram for potash-soda-felspars for temperatures down to 800° C.

These compositional changes in the crystallizing felspars proceed in the opposite direction from those which usually produce phenocrysts by the removal of the component in excess of the eutectic or cotectic ratio. For example, a magma having the initial composition of PP_1 and with sufficient fluxes and mineralizers to form a first cotectic at a temperature T_1 , would begin to form phenocrysts of potash-soda-felspar of composition Q at a temperature T . As the temperature fell towards T_1 successive crystallizations would follow the composition line QR with increasing soda-content. Any further drop in temperature below T_1 would be of the cotectic type, with simultaneous crystallization of potash-rich and soda-rich members, as indicated above. The potash-rich crystals separating would now follow the composition line RN with decreasing soda-contents, as the temperature fell from T_1 to T_2 .

(c) *Application of the thermal diagram to granite magmas.*

In his first thermal diagram for potash-soda-feldspars, Vogt (35, pp. 529-535) fixed the eutectic ratio for granitic rocks at 42 % potash-feldspar, and the immiscibility gap between 12 and 72 % of that component. In his latter publications the immiscibility gap is made to depend on the 'cotectic' crystallization temperature and the amount of silica and fluxes present, but the same cotectic ratio is maintained, only slightly modified by the presence of much anorthite. Vogt believes that granite magmas have been derived from more basic magmas by differential crystallization (following the thermal diagrams) with the residual feldspars tending towards the cotectic ratio as crystallization proceeds (38, pp. 230-241).

Bowen (10) arrives at similar conclusions from the experimental evidence obtained from the ternary equilibrium systems. He shows that dry melts containing free silica and an alkali aluminosilicate, with lime, magnesia, or iron as the third component, become, by a process of fractional crystallization, enriched in alkali aluminosilicates. The same process acting on a mixture of all these components would concentrate the alkali aluminosilicates in the residual liquid, thus tending towards the ternary system $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-SiO}_2$, which Bowen considers to be the 'residua' system of petrogeny. The equilibrium diagram for this system by Schairer and Bowen (29) is reproduced in fig. 5 (p. 98). Bowen regards the oblong belt or trough of low melting temperatures (*abcd*) as a 'sink' towards which the alkali aluminosilicate-silica residues of rock magmas tend to converge. Most phonolites, trachytes, and rhyolites, when reduced to an alkali aluminosilicate-silica basis (and they usually contain well over 80 % of these constituents) lie within the belt (*abcd*), and the same applies to many syenites and granites. These rocks have crystallized at temperatures well below the lowest isotherms of fig. 5 and their position in the 'sink' indicates that the depression of the melting-point surfaces by fluxes and mineralizers has not caused the cotectic lines appreciably to deviate.

The potash-granites, however, lie well outside the 'sink', just as they lie on the *wrong* side of the cotectic line of Vogt. Bowen (9, pp. 227-231) accounts for these by assuming that the relation between orthoclase and anorthite is not of the eutectic kind, but a 'reaction' with no minimum.¹

¹ The formation of mantles of orthoclase around basic plagioclase, which Bowen considers to be due to a 'reaction' process, may possibly be due to other causes, e.g. supercooling. The reverse arrangement of oligoclase borders to orthoclase (rapakivi granite, &c.) is definitely not a 'reaction' relationship.

As a consequence he makes the Or, Ab, An cotectic line lie nearer the Or-Ab side than does Vogt. Doggett (15), from a consideration of many rock analyses, also makes the cotectic line lie nearer the orthoclase-albite join.

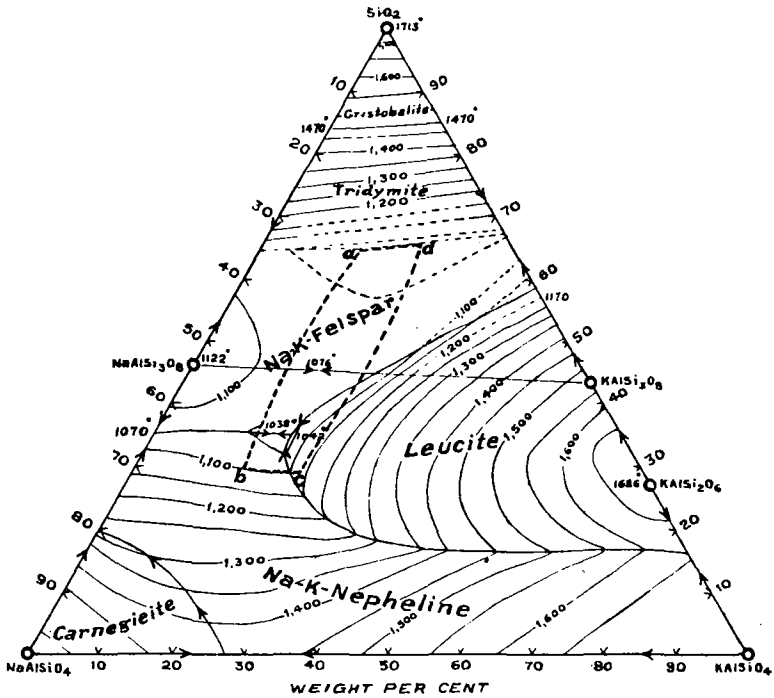


FIG. 5. Equilibrium diagram of the system $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 - SiO_2 .
After J. F. Schairer and N. L. Bowen, 1935 (29, p. 326).

Vogt (38, pp. 220-229) has criticized these views, pointing out that, according to Bowen's diagram, orthoclase could crystallize before plagioclase only over a very limited range of composition, whereas, in potash-granite, orthoclase occurs as primary phenocrysts over a much wider range. He holds that these highly potassic granites have been produced by myrmekitization and late stage magmatic reactions within the more basic magmas, before a separation by 'filter-pressing'.

Recently, Doggett (16) has pointed out that such reactions would involve a departure from Vogt's binary diagram, and suggests that a deviation of the cotectic line towards the potash side with increasing

amounts of fluxes might explain the potassic enrichment. It is suggested that this is implied in Vogt's discussions of these magmas, although his various cotectic diagrams (37, pp. 88-91) with nearly constant feldspar ratio are at variance with this view.

Whatever their origin, these potash-rich rocks provide perhaps the best example of crystallization according to the normal binary diagram with immiscibility gap, i.e. the excess potash has been eliminated as phenocrysts of orthoclase or microcline, while the composition of the residual magma has moved toward the 40:60 potash:soda-feldspar ratio. It follows that either of the above explanations (myrmekitization, or a deviation of the cotectic line) could represent only a temporary aberration of the normal sequence of crystallization, and it does not seem possible that with gradually falling temperatures the sequence could oscillate in this manner, or vary so abruptly without apparent cause.

(d) *The composition of granite-pegmatites.*

The origin of the granite-pegmatites is even less satisfactorily explained by the thermal diagram than is that of the potash-rich granites. Derived from the residual magmas of the granites with which they are associated, the pegmatites, according to Vogt's diagram, should have a composition closer to the cotectic ratio than the parent granite, whereas they are usually more potassic.

Owing to the very coarse character of most granite-pegmatites, few *average* chemical analyses are available, but there is much evidence to show that they are predominantly potassic rocks. For instance, descriptions and statements by Vogt (38, pp. 68-73), Mäkinen (25), Derry (12), and Fersman (18) all emphasize the dominantly potassic nature of these rocks. Landes (23, p. 96) states that the volume of the complex albite-bearing pegmatites is almost negligible in comparison with that of the 'simple' quartz-microcline-muscovite type.

Granite-pegmatites examined by the writer in many localities in India also show this preponderance of potash-soda-microcline. For instance, in the Kodarma mica-mining area, Bihar, pegmatites occur both in a granite-gneiss ('dome-gneiss' of the Survey) and in the country schists. In the gneiss occur quartz-microcline-muscovite-pegmatites with subordinate albite-oligoclase, corresponding to the 'simple' pegmatites of Landes. The microcline usually consists of mixtures of 'film' and 'vein' perthite; in some cases it is graphically intergrown with quartz, but in others it is coarsely crystalline and idiomorphic. Where albite-oligoclase occurs in these 'simple' pegmatites, it seems to have crystallized

idiomorphically before the quartz-microcline graphic structures. It never occurs as a ternary eutectic. Thus the tendency of the residual potash-rich pegmatite magma is towards a still more highly potassic ratio.

In the country-rocks, both 'simple' and 'complex' pegmatites occur, with predominant microcline and albite-oligoclase respectively. In the former type, microcline, quartz, and muscovite are associated with subordinate albite-oligoclase and varying quantities of biotite, tourmaline, garnet, apatite, and other accessory minerals. The microcline is of the composite 'film' and 'vein' perthite type, sometimes as crystals two or three feet in length. Fine and coarse graphic intergrowths with quartz occur.

The plagioclase-rich pegmatites consist mainly of quartz, albite-oligoclase, and muscovite, with accessory tourmaline, garnet, apatite, and beryl. The albite-oligoclase is sometimes of the hydrothermal cleavelandite variety and is frequently associated with a greenish-yellow mica resembling gilbertite. Quartz, plagioclase, and muscovite are coarsely (and often regularly) intergrown, but no graphic intergrowths of quartz and plagioclase were noted.

Many of the larger pegmatites appear to be mixtures of the above two types; it is probable that the soda-rich portions have been formed by the albitization of previously intruded microcline-quartz-muscovite-pegmatite.¹

Quantitatively, the Kodarma pegmatites are predominantly potassic, the majority being of the 'simple' quartz-microcline-muscovite type. Where the soda-felspar is present in more than subordinate amounts, it occurs almost to the exclusion of the potash-felspar. There is nothing approaching the 40:60 potash:soda-felspar ratio of Vogt's residual magma.

(e) Cause of the potassic enrichment of granite-pegmatites.

Vogt (38, pp. 89-91) considers that myrmekitization and late-stage reactions in the residual granite magma followed by 'filter-pressing' would account for the potassic nature of granite-pegmatites. This explanation really involves a modification of the binary felspar diagram. If, as Vogt assumes, this is a temporary modification caused by the special conditions of late-stage crystallization, the removal of the pegmatite magma should be followed by a return to normal conditions of crystallization, with impoverishment in potash, but the field evidence

¹ Cf. Schaller (30, pp. 274-279).

points to a further enrichment in potash during the crystallization of pegmatite.

Doggett's suggestion of a movement of the cotectic line towards the potash side, with increasing amounts of fluxes, has the merit of simplicity. The end of this process would be the formation of quartz-microcline graphic structures, which would represent a ternary cotectic with the 'vein' perthite as the plagioclase component.

Such a deviation of the cotectic line from the 40:60 ratio of the granite residual magma to 70:30 in the final graphic pegmatite would require the removal by crystallization of about 70 % of the original soda-component as albite-oligoclase, either in the granite or the early pegmatite crystallization, or in both. If most of this change took place in the last stages of crystallization of the granite, the average composition of that rock might not be seriously affected because of its relatively large mass in comparison with the residual magma. But the deviation of the cotectic line would then be extremely sharp for such a small drop in temperature. On the other hand, the field evidence does not support the view that any large portion of this excess albite separated in the early stages of crystallization of the 'simple' pegmatites. Moreover, the complex albite-bearing pegmatites demand a late-stage, partly hydrothermal, soda-rich magma, certainly out of keeping with a deviation of the cotectic line to the potash side.

Beskow (8), Goldschmidt (20), and others have accounted for soda-enrichment by the elimination of potash in the form of biotite, instead of, or in addition to, potash-felspar, particularly in water-rich magmas. While this process, and myrmekitization or a deviation of the cotectic line, may have produced soda-rich and potash-rich magmas respectively, they could not have been active at the same time, nor is it likely that one process could have immediately followed the other. Hence we must look for some other explanation of the frequent occurrence of both potash- and soda-rich pegmatites in association with the same granite intrusion.

(f) Immiscible potash- and soda-rich magmas.

The writer suggests that these apparently conflicting data can be harmonized by assuming that, during the later stages of the crystallization of the granite, the residual magma separated into two fractions of gradually increasing immiscibility, one very rich in soda, the other rich in potash but containing some soda. The latter would represent the magma of ordinary granite-pegmatites.

Liquidity in this temperature region—about 400–1000° C. below the melting-points of the three principal components, and 300–400° C. lower than that of their 'dry' eutectic—is only possible in the presence of considerable quantities of fluxes and mineralizers. Immiscibility in such a magma is a more logical development of the higher-temperature cotectic diagram than a re-solution of orthoclase or a diversion of the cotectic ratio.

It simply means that the rapidly decreasing mutual solubility of the two solid feldspar phases—brought about by falling temperature, and possibly accentuated by a change to the microcline form—has extended to the liquid phase. In the same way that at higher temperatures the intersection of the solidus-liquidus with the exsolution curve inhibits the formation of a single homogeneous feldspar phase from a magma of binary cotectic composition, so its intersection with the immiscibility curve would prevent the crystallization of the single quartz-orthoclase-albite cotectic, and give rise instead to two separate cotectic magmas.

Assuming that the potash:soda-feldspar ratios in the potash-rich and soda-rich phases are of the order of 60:40 and 10:90, the relative proportions of the two phases produced from a magma of cotectic ratio 40:60 would be approximately as three is to two; i.e. the potash-rich phase would be in excess. This partial magma, largely removed by 'filter-press action', would give rise to the 'simple' granite-pegmatites.

The soda-rich magma, smaller in quantity and possibly denser, might follow the channels taken by the potash-rich fluids, to give rise to albitization and the 'complex' pegmatites. It would also tend, in part, to remain between the crystals of the partly consolidated granite, there to give rise to myrmekite, deuteric perthite, and similar structures, which are often regarded as products of late-stage magmatic reaction.

Although many writers (e.g. Sederholm (32), Schaller (31), and Gilluly (19)) have considered myrmekite to originate through secondary replacement, others claim for it an origin in direct crystallization. The Indian charnockites are rich in myrmekite, and my examination of many of them shows that the myrmekite boundary—which is usually curved and sometimes totally enclosed by orthoclase—cuts sharply across the microperthitic structure. This indicates that the myrmekite was formed before perthite exsolution took place, i.e. above 400° C. and probably not below 600–700° C.

Becke (7, pp. 384–390) showed that the amount of quartz in myrmekite increases with the anorthite content of the plagioclase. He suggested

that in the replacement of potash-felspar by plagioclase, silica was liberated in proportion to the amount of lime present in the latter.

The same variation of the quartz would also result from the crystallization of plagioclase from a residual magma rich in soda and lime, if the amount of excess silica and water were controlled by the metallic oxides present, rather than by the felspar ratio. I have found nothing in the Indian charnockites inconsistent with the view that the myrmekite has crystallized directly from an albite-rich phase produced by immiscibility on the lines indicated above.

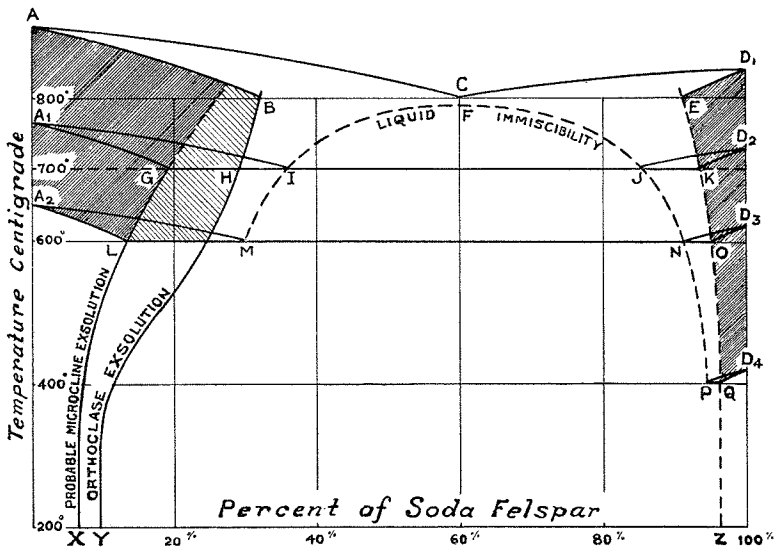


FIG. 6. Suggested cotectic diagram for potash-soda-felspars for temperatures below 800° C.

(g) Diagram illustrating liquid immiscibility.

Fig. 6 extends the thermal diagram of fig. 4 to show liquid immiscibility below 800° C. The curve *MFN* limits the field of complete miscibility; the exsolution curve for orthoclase below 800° C. is *BHY*, and for microcline, *GLX*. According to this diagram; a magma of cotectic composition at 800° C., if further cooled (with continuous separation of potash- and soda-felspars and quartz), would gradually separate into two immiscible magmas, with the compositions *I* and *J* at 700° C. and *M* and *N* at 600° C.

Consider first the potash-rich magma. The solubility of the soda-

component in the solid potash-felspar at a temperature of 700° C. is represented by *H* for the orthoclase and by *G* for the microcline form. There is a tendency in this temperature region for microcline to separate, so the solidus-liquidus curve has the form A_1GIF . When microcline of composition *G* forms, the magma is enriched in soda by an amount *GI*. This excess of soda might add to the immiscible soda-magma *J*, it might form albite-oligoclase of composition near *K*, or it might form 'vein' perthite within the microcline, depending upon the pressure, the rate of cooling, and the rate of elimination of volatile fluxes. At 600° C., approximately the temperature of final crystallization of the quartz-microcline graphic cotectic, the felspar ratio in the magma corresponds to *M* and the microcline separating out has the composition *L*. The microcline in the graphic cotectic would contain up to $LM\%$ of albite-oligoclase as 'vein' perthite, depending upon how much is removed as a late-stage hydrothermal albite-rich magma.

The crystallization of the soda-rich fraction would follow similar lines, but the proportion of the potash-component present would be small. Field evidence suggests that the residual portion of this soda-rich magma collects more of the volatiles and nearly all the rare elements, and that it retains fluidity to a considerably lower temperature than does the potash-rich magma.

The above explanation accounts for the narrow range of composition of graphic structures, 'vein' perthite, and true myrmekite better than any theory of origin by replacement. Below a certain temperature, immiscibility would demand the formation of binary quartz-microcline or quartz-plagioclase cotectics, rather than the ternary quartz-microcline-plagioclase cotectic required by the diagrams of Vogt and of Schairer and Bowen. It cannot be accident that these binary cotectics frequently occur in pegmatites, while the ternary cotectic is apparently absent. Granite-aplites, granophyres, and microgranites sometimes approach the latter in composition, but they probably represent rapidly cooled, high-temperature magmas.

Sundius (34) has recorded the occurrence of two types of aplite in association with the Lofthammer granite which he believes to have been produced by immiscibility from a parent granite magma. One type is red and potassic and the other—which occurs in much smaller quantities—is white and albitic. Myrmekitization is common in the granite and in the red aplite. Askund (5) has also described a granite-norite rock suite in the neighbourhood of Stavsjö, which in his opinion has been developed by a process of liquid separation.

Bowen (9, pp. 13-16) objects to the view that immiscibility has caused differentiation in rock-magmas, partly on the ground of negative evidence, viz. the absence of globules of the differentiate in glassy rocks, and the absence of a discontinuity at the crystallizing surfaces. If liquid separation has occurred, as is suggested here, in the later stages of the consolidation of the granites, the slow cooling and coarse crystallization would obliterate such traces of immiscibility. Nevertheless, it is possible that many 'deuteric' and 'vein' perthites and myrmekitic structures may represent residual portions of immiscible magmas.

Greig (21) has shown that although some of the silicates of lime and magnesia form immiscible mixtures, the silicates of potash and soda are completely miscible. It must be remembered that in the pegmatite magmas we are dealing not with simple silicates, but with aluminosilicates in the presence of excess silica and fluxes at temperatures very much below the dry melting-point. It may be significant that the immiscible systems described by Greig contained high concentrations of silica.

IV. QUARTZ-MICROCLINE GRAPHIC STRUCTURES.

The somewhat narrow range of composition of quartz-microcline graphic structures was first noted by Mäkinen (25, p. 30), who found that the ratio of quartz to microcline varied between 23:77 and 32:68. Vogt (38, p. 125), from a study of the Norwegian pegmatites, concluded that these structures represented the final simultaneous crystallization of a quartz-microcline cotectic in the presence of silica solutions and mineralizers at a temperature of 600-640° C. He refers to Fersman's proof of the simultaneous crystallization of quartz and microcline (17) and shows that quartz, in his own specimens, varies only between 20 and 25 %, with a mean of 23 %, whilst the proportion of (Ab+An) has the same range as that of ordinary pegmatitic microclines.

Five Indian specimens (from Kodarma in Bihar and Jointora in Orissa) of quartz-microcline graphic structures show a slightly wider range of free quartz (15 to 26 %), with an average of 20 %. The microcline averaged 20 % of soda-lime-felspar, with an extreme range of 13 to 31 %. On the whole, these specimens tend to support the view that the structures have a limited compositional range.

Vogt, as mentioned above, considers that these structures are binary cotectic crystallizations. The writer suggests that they represent the last stage of potassic enrichment which began in the separation of the granite residual magma into immiscible sodic and potassic fractions.

Falling temperatures, and changes in the amount of silica and fluxes present, caused the latter fraction to become further enriched in potash, with the final separation of the quartz-microcline graphic structures.

V. THE ORIGIN OF 'VEIN' PERTHITE.

The coarse, irregular variety of perthite generally associated with the microcline of pegmatites and the finer 'exsolution' perthite were both referred to by Warren (41, p. 129), who considered the coarse 'vein' perthite to be formed by direct crystallization or in the early stages of exsolution, and the finer 'film' perthite during or after the transformation into microcline.

Andersen (4, pp. 149-153), who suggested the term 'vein' and 'film' or 'string' perthite for the two forms, considers that the former may have been produced by the infiltration of albite-bearing solutions into the host feldspar, along shrinkage cracks nearly perpendicular to the *a* crystallographic axis. He cites the experiments of Kôzu and Saiki (22) on the thermal expansion of six specimens of potash-soda-feldspar. These workers found that the coefficient of expansion in the direction of the *a*-axis between 0° and 1000° C. was greater than in the directions of the *b*- or *c*-axes. The expansion along the *a*-axis was 2 %, while the mean value in the direction of the *b*- and *c*-axes was 0.6 %. A detailed examination of these results gives less support to the hypothesis of shrinkage cracks than Andersen claims. One of Kôzu and Saiki's specimens was adularia, which should be excluded from the present discussion as it has been formed below 400° C. and contains no 'vein' perthite, yet its high expansion ratio of 8:1 has raised the average. Similarly, Ceylon moonstone (also mentioned in the experiments) has an expansion ratio of 6:1, although this and other soda-rich feldspars formed at relatively high temperatures show no evidence of shrinkage cracks and rarely contain 'vein' perthite.

In addition, the temperature range through which contraction can have been effective in pegmatitic microcline (the true host of 'vein' perthite) extends only from 750° to 350° C., much less than the experimental range of 0° to 1000° C. This very much reduces the possible volume of shrinkage cracks. Other objections to this view of the origin of 'vein' perthite by replacement or infiltration are as follows:

1. The (Ab+An) content of the microcline which bears 'vein' perthite is never more than about 30 %. If we allow 6 to 14 % for the 'film' perthite invariably present, it is clear that 'vein' perthite can never exceed 20 to 25 %, whereas the maximum possible replacement by soda-

felspar would be about 86 to 94 %. This in itself is strong evidence against a replacement or secondary infiltration origin for the 'vein' perthite.

2. In most specimens the 'vein' perthite is in optical continuity with the microcline, i.e. the albite-twin lamellae of the perthite lie parallel to those of the microcline. One would expect this to be the case if crystallization of the microcline and perthite had been simultaneous, but not necessarily so if the albite were of later infiltration origin.

3. The 'vein' perthite grades in size from about 2 mm. maximum thickness in some specimens to near the dimensions of the 'film' perthite (0.001 mm. thick) in others; when it approaches the latter's regularity of form and distribution. It is doubtful whether infiltration could produce such regularly arranged and finely divided albite films.

4. The widespread occurrence of 'vein' perthite in the microcline of ordinary granite-pegmatites (which usually show no evidence of albitization) is against an origin by replacement.

5. In quartz-microcline graphic structures the 'vein' perthite shows no tendency to follow the quartz-microcline junctions, and ignores the graphic structure, whatever the size of the latter. Shrinkage cracks produced in the microcline on cooling should have fractured the interlocking quartz plates and strings in various places, and so have allowed 'cross-veins' of perthite to form. The 'vein' perthite is never seen to cross the quartz bands in this manner, or even to corrode them. To some extent the size and form of the 'vein' perthite appears to be regulated by the size of graphic structures.

6. There is definite microscopic evidence that the coarseness of the cross-hatch twinning in the microcline has been affected, or regulated, by adjacent 'vein' perthite, and in some cases by adjacent graphic quartz. For secondary albite to produce this effect there must be a concomitant reconstitution of the host microcline. The regularity of the film or exsolution perthite in these areas is against such a reconstitution having taken place.

To overcome these difficulties the writer suggests that 'vein' perthite has been formed by the simultaneous crystallization of the 'vein' albite and the host microcline (together with quartz in the case of the graphic structures). The magma of the simple pegmatites, in which typical 'vein' perthite almost invariably occurs, has been shown (see p. 102) probably to be the immiscible potash-rich fraction derived from an original granite magma. The present explanation of 'vein' perthite suggests that the 30-40 % of soda-component held in solution in this

potash-rich magma, less the amount (6–20 %) in solid solution in the crystallizing microcline, has separated, in the main, simultaneously and in optical continuity with the microcline as coarse albite-oligoclase lamellae, either in the early pegmatitic crystallization, or later in the graphic structure.¹

If the above explanation is correct, the term “‘vein’ perthite’ leaves something to be desired. Alling’s ‘eutecto-perthite’ is better (3, p. 48), but perhaps the term ‘cotecto-perthite’ would more correctly express the relations of this variety of albite blebs.

VI. EFFECTS OF PRESSURE ON THE EXSOLUTION CURVE.

It was assumed (see above, p. 90) in discussing the exsolution curve in relation to temperatures of formation, that experimental results obtained at atmospheric pressure could be applied without correction to natural conditions. This assumption may not introduce serious errors for lavas and most pegmatites, but for deep-seated rocks formed under high pressure a correction will be necessary. We have seen that a considerable increase in volume takes place during the solution of microperthite, and it may be inferred that high pressure would tend to reduce the amount of solid solution at any given temperature.

In this connexion consider the Clausius-Chapeyron equation $\delta t/\delta p = 10.33 (V_1 - V_2) T/E.Q$, where $\delta t/\delta p$ is the change in melting-point of a solid (in degrees Centigrade) for unit increase of atmospheric pressure. T is the melting-point of the solid on the absolute scale. $(V_1 - V_2)$ is the difference in specific volume between liquid and solid at the melting-point, and Q is the latent heat of solution in gram calories per gram. E is a constant and equals 425. For microperthite solid solutions $(V_1 - V_2)$ may be taken as the difference in specific volume between the two phases of the soda-component, i.e. when it is in complete solid solution in the potash-felspar, and when it is separated as albite lamellae. The specific gravity of pure albite is 2.628 and that of pure orthoclase is 2.588. The specific gravity of the potash-felspar is increased by about 0.002 for every 10 % of soda-felspar dissolved in it. The difference in specific gravity between the dissolved and albite form of soda-felspar is thus approximately $2.628 - (2.588 + 0.020)$, and the value of $(V_1 - V_2)$ becomes $2.628 - 2.578/2.628 \times 2.578$ or very nearly 0.008.

The value of Q is at present undetermined. Dittler and Köhler

¹ This does not preclude the occurrence of ‘vein’ perthite of secondary origin, but it does suggest that the commonly occurring, regularly arranged ‘vein’ perthite of granite-pegmatites is a contemporaneous product.

(14, p. 260) tried to measure the heat of solution of perthite by a differential method, but without success. It is probable that Q will be of the same order of magnitude as the latent heat of inversion of α - to β -quartz, which, according to Wright and Larsen (42), is about 4.3 ± 1 calories. For calculation we may assume that Q is 5 calories per gram at the crystallizing temperature of 800°C . $\delta t/\delta p$ then becomes $10.33 \times 1073 \times 0.008/425 \times 5 = 0.0418$. This implies a rise in the temperature of exsolution of about 40°C . for a pressure of 1000 atmospheres, which is of a higher order than that calculated by Vogt (36) for the rise in the crystallization temperature of rock magmas, viz. 4° to 10°C . for 1000 atmospheres.

Thus, for deep-seated rocks, where pressures of the order of 10,000 atmospheres may occur, the modification of the exsolution curve will be large. The final effect will be to raise that part of the curve between 10 and 40 % soda-component into the higher temperature region, and at the same time make the slope steeper. As a result, phenocrysts will form with less soda-component—for a given crystallization temperature—than is shown by the exsolution curve of fig. 3. At the same time conditions will be less favourable to the formation of the microcline form because of the reduced amount of exsolution and the less oblate form of the indicatrix of the crystalline feldspar.

How far does petrological evidence support these conclusions? If, as Vogt estimates, granites have crystallized between 950° and 800°C ., the amount of soda-component in the potash-feldspar should be of the order of 30 to 40 %, assuming the crystallization to have taken place under atmospheric pressure. But many porphyritic granites contain phenocrysts with distinctly lower soda-contents than this, even when the potash-soda-feldspar content of the rock approaches the 40:60 cotectic ratio. As instances, we may consider Dartmoor granite, with phenocrysts approximating to $\text{Or}_{71}\text{Ab}_{27}\text{An}_2$; Shap granite, with phenocrysts of $\text{Or}_{73.5}\text{Ab}_{24}\text{An}_{2.5}$,¹ and Peterhead quartz-porphyry, with phenocrysts of $\text{Or}_{79}\text{Ab}_{20}\text{An}_1$. The porphyritic feldspars of these three rocks are orthoclase-micropertthites.

The garnetiferous gneissose granite of Kalahandi, Orissa, India, from which specimen E (see tables I and II, Part I) was obtained, provides another good example. This rock is exposed intermittently over a belt of country some 16 miles wide by at least 100 miles long (Walker, 40,

¹ Vogt (38, p. 203) refers the Shap phenocrysts to microcline, but specimens which I have collected and examined show no trace of cross-hatch twinning on (001), while the optic axial angle ($2V\ 60^\circ$) is that of normal perthitic orthoclase.

pp. 6-7). Samples collected by me contain up to about 30 % of fresh micropertthitic orthoclase phenocrysts, several inches across, and usually in the form of Carlsbad twins. The groundmass consists of plagioclase, orthoclase-micropertthite, garnet, and biotite, with hypersthene and quartz as accessories. The composition of the plagioclase is approximately $Ab_{45}An_{55}$.¹ Sufficient soda is present to ensure the saturation of the early-formed orthoclase phenocrysts, yet they contain only 14 % of this component. Analyses of the rock, and of the matrix, freed as far as possible from the porphyritic feldspars, are given below.

	(a)	(b)
SiO ₂	63.78	61.90
TiO ₂	1.17	1.60
Al ₂ O ₃	16.21	15.00
Cr ₂ O ₃	nil	nil
Fe ₂ O ₃	0.60	1.04
FeO	4.93	8.06
MnO	0.11	0.19
MgO	1.27	2.22
CaO	3.84	5.21
SrO	nil	n.d.
BaO	0.20	n.d.
Na ₂ O	1.82	1.68
K ₂ O	5.16	2.18
H ₂ O+110° C.	0.46	n.d.
H ₂ O-110° C.	nil	n.d.
CO ₂	0.05	n.d.
SO ₃	0.08	n.d.
P ₂ O ₅	0.25	n.d.
Cl	0.017	n.d.
Total	99.95	99.08

(a) Garnetiferous granite-gneiss. From railway cutting and quarry, near Ombadwla, Kalahandi State, Orissa, India.

(b) The matrix of the above rock, after the removal of the porphyritic feldspars. Same locality.

All chemical analyses given in this part and in the first part of the paper are by E. Spencer and K. B. Sen, unless otherwise stated.

VII. HIGH-TEMPERATURE PEGMATITES.

Although most pegmatites have probably crystallized between 500° and 800° C., field and laboratory evidence both suggest that the soda-rich feldspars of the Ceylon moonstone pegmatites, the Mogok, Burma, gemstone pegmatites, and the Fredriksvärn pegmatite must have crystallized at higher temperatures. The exsolution curve *ABCD* of fig. 3

¹ I am indebted to Mr. W. D. West of the Geological Survey of India for this determination of the plagioclase on the universal stage.

shows that feldspars of these compositions (about 30 to 50 % of Ab + An) must have been formed at not less than 900° C.: even low pressures would raise the temperature to the order of 1000° C. for the more sodic forms.

The common association of these pegmatites with gemstones such as ruby, sapphire, zircon, and spinel, the very small quantities of ferromagnesian minerals present, the relatively small proportion of free quartz, and the almost complete absence of mica all point to the presence of only small quantities of fluxes and to a high temperature of formation.

VIII. SYNGENETIC FELSPARS FORMED BY SOLID STATE DIFFUSION.

The potash-soda-feldspars described in this paper all belong to rocks of magmatic origin. This is indicated by their field relationships and by their behaviour to heat-treatment. Except for one or two microclines which show a little 'vein' perthite, all the specimens can readily be made homogeneous by heating, and were undoubtedly so at the time of their formation.

There are, however, alkali-feldspars which were not formed by crystallization from a magma. Apart from the authigenous feldspars formed in unaltered, or only slightly altered, sedimentary rocks, there is much to show that feldspars may form under conditions of thermal metamorphism at temperatures below the melting-points of any of the rock constituents.¹ One strong line of evidence is the common occurrence of phenocrysts (porphyroblasts) of potash-soda-feldspar in semi-pelitic xenoliths, sometimes when the latter still retain their original bedding or schistosity, showing that the xenolith remained solid.

The composition of the xenoliths precludes a simple origin by molecular reconstitution for the feldspar porphyroblasts. It is possible that the silica and alumina may have been more or less in situ, but the potash and soda must have been locally concentrated by migrating solutions or by solid diffusion. The second process may in some ways resemble the migration of ions referred to in connexion with the formation of perthite (see Part I, p. 485). If this latter view is correct, the silico-alumina framework in certain parts of the xenolith may have acted as a one-way 'sink' towards which any potassium or sodium ions would migrate to form an alkali-feldspar structure.

These porphyroblasts must have been formed in a relatively short time as compared with the total time of magmatic consolidation and metamorphic action. It is possible that the same process acting over long periods might produce holocrystalline rocks with more or less com-

¹ See, e.g., A. Brammall (11, pp. 97-98.)

plete obliteration of the original structure, without the mass having reached even a plastic condition. How far such a process might have given rise to granitic and similar rocks is outside the scope of this discussion, but it might be worth while to consider the characters of alkali-felspars formed under such conditions.

One would expect such crystals to be less homogeneous than those formed from magmas, owing, firstly, to unassimilated non-felspathic material, and secondly, to the lessened mutual solubility of the two felspars at lower temperatures. Any excess of soda-component, for example, over the composition represented by the solid saturation point for that particular formation temperature, would form parallel growths or some crude form of perthitic structure, easily distinguishable from exsolution perthite, or regular 'vein' perthite. Microperthite of exsolution origin would be of less frequent occurrence than in felspar formed from magmatic crystallization, but where found, the composition should correspond to the exsolution curve for the particular formation temperature.

The large felspars in xenoliths in the Shap granite, many of which I have examined, show the same homogeneous structure (with fine exsolution perthite) as do those of the surrounding granite. One crystal was found to have an optic axial angle $2V\ 61^\circ$, the same as those of phenocrysts from the granite. In chemical composition the felspars of the granite and of the xenoliths are almost identical (see analyses below).

	(a)	(b)	(c)
SiO ₂	64.60	64.28	68.58
TiO ₂	—	—	0.66
Al ₂ O ₃	19.38	19.40	14.34
Fe ₂ O ₃	0.22	0.34	2.00
FeO	—	—	2.34
MnO	—	—	0.23
MgO	trace	trace	1.58
CaO	0.28	0.48	1.68
Na ₂ O	2.78	2.74	3.04
K ₂ O	11.78	11.80	4.80
H ₂ O + 110° C.	—	—	0.34
H ₂ O - 110° C.	—	—	0.15
CO ₂	—	—	0.06
Loss	0.70	0.58	—
Total	99.74	99.62	99.80

(a) Orthoclase porphyroblast from semi-pelitic xenolith in granite. Shap quarry, Westmorland. $Or_{69.62}Ab_{23.50}An_{1.40}$.

(b) Orthoclase phenocryst from Shap granite, Shap quarry, Westmorland. $Or_{69.74}Ab_{23.16}An_{2.40}$.

(c) Porphyritic granite (adamellite). Shap quarry, Westmorland.

Some of the porphyroblasts show an oscillatory zoning of the microperthitic structure. Whether these crystals have been formed in situ in the xenolith, or have been introduced bodily from without, it is clear that their temperature of formation has been very little lower, if at all, than that of the associated granite magma, and certainly not lower than that at which orthoclase of composition $Or_{74}Ab_{24}An_2$ becomes homogeneous, i.e. not less than about 700–800° C.

Another specimen, kindly supplied to the writer by Dr. A. Brammall, is a xenolith of Malmesbury shale in the Kloof granite, Cape Town. This xenolith has a banded structure and a dark grey colour, and contains porcelain-white feldspars up to one and a half inches across. Some of the crystals have incompletely formed outlines and most of them contain unassimilated non-feldspathic material. One large crystal was found to have the composition $Or_{70}Ab_{27}An_3$. It was too heterogeneous for refractive index determination, but a fairly clear fragment had an optic axial angle of about $2V\ 77^\circ$.

Sections on (010) display a coarsely perthitic arrangement of potash- and soda-feldspar much more irregular than the usual 'vein' perthite. In addition, a very fine exsolution microperthite is visible in the potash-rich areas. Sections on (001) show the same coarse, irregular perthitic structure, and also evidence of the cross-hatching of microcline.

The presence of microperthite of exsolution origin in these porphyroblasts shows that they were formed at a temperature above 400° C. On the other hand, the presence of unassimilated, coarsely perthitic albite-oligoclase indicates a formation temperature lower than that of the crystallization of granite magmas. The amount of soda-feldspar present as coarse perthite is about 20 %, leaving about 10 % to be accounted for by the fine exsolution microperthite. This suggests that the formation temperature of these crystals has been nearer the lower than the upper limit of the 400–800° C. exsolution temperature range.

Phenocrysts separated from the associated Kloof granite also show similar coarse perthite and unassimilated non-feldspathic material, but the coarse perthite is more regular, and apparently smaller in amount, than in the crystals from the xenolith. Exsolution microperthite is visible in the potash-rich areas, which also show microcline twinning.

Sections of the groundmass of the xenolith show a coarsely banded arrangement of plagioclase, orthoclase, muscovite, biotite, and quartz. The average composition of the xenolith is similar to that of a potash-rich granite (see analyses below, and compare with the analysis of Shap

granite). The potash-soda-lime ratio, calculated as feldspar, is approximately $\text{Or}_{54}\text{Ab}_{40}\text{An}_6$.

	(a)	(b)
SiO_2	64.80	67.03
TiO_2	—	0.63
Al_2O_3	19.87	16.66
Fe_2O_3	0.25	0.48
FeO	—	3.96
MnO	—	0.27
MgO	0.26	1.84
CaO	0.48	0.70
Na_2O	3.04	2.59
K_2O	10.96	5.13
$\text{H}_2\text{O} + 110^\circ \text{C.}$	—	0.49
$\text{H}_2\text{O} - 110^\circ \text{C.}$	—	0.11
CO_2	—	nil
Loss	0.70	—
Total	100.36	99.89

(a) Orthoclase porphyroblast from xenolith of Malmesbury shale in Kloof granite, Cape Town, South Africa. $\text{Or}_{64.75}\text{Ab}_{25.69}\text{An}_{2.40}$.

(b) Banded xenolith of Malmesbury shale in Kloof granite, Cape Town, South Africa.

It is interesting to observe that if the metamorphism of this particular xenolith had been carried to the stage of complete holocrystalline reconstitution, with homogenization of the feldspar porphyroblasts, but without actual fusion, the result would have been a rock closely resembling—if not identical with—a porphyritic potash-rich granite. The possibility that such rocks may be derived by metamorphism, well below the solidifying temperatures of igneous rocks, indicates the difficulties of the problem, and the need for caution in the use of crystallization diagrams where there is not convincing field evidence of the magmatic origin of the rock in question.

IX. SUMMARY.

The common occurrence of the microcline form of potash-soda-feldspar in pegmatites may be due to the crystallization temperature of the latter falling within the perthite exsolution range. At these relatively low temperatures the oblateness of the indicatrix is a maximum, and this, together with the fact that exsolution and crystallization of the two feldspars are taking place simultaneously, provides the optimum conditions for the formation of microcline. The parallel orientation of the albite and the microcline twinning in coarsely perthitic microcline supports this view.

The derivation of the common potash-rich pegmatites from granite magmas cannot be satisfactorily explained by the existing binary or ternary crystallization diagrams. To overcome the various difficulties, the writer suggests that the residual granite magma has separated into two fractions, one rich in potash, which produced the ordinary pegmatites, the other rich in soda, which produces the complex pegmatites, and possibly much of the myrmekite of granites. This suggestion involves a modification of the binary diagram for temperatures below 750–800° C., and accounts for the following facts:

1. The potash-rich character of the ordinary pegmatites, and their preponderance over the complex albite-rich pegmatites.
2. The final graphic cotectic of quartz and microcline, or alternatively, of quartz and oligoclase.
3. The absence of the ternary graphic cotectic of quartz, microcline, and plagioclase from these low-temperature crystallizations.
4. The quartz-oligoclase cotectic composition of the myrmekite of granites, on the assumption that some part of the albite-rich immiscible magma has been retained in the crystal mush.
5. A last-stage albite-rich magma which gave rise to the complex pegmatites.

This view of two immiscible magmas derived from a common granite magma has been put forward by other workers to explain special field problems.

Microperthitic exsolution causes an increase in density. Very high pressure would tend to promote exsolution and so modify the exsolution curve, and indirectly, the binary cotectic crystallization diagram, by increasing the immiscibility gap. Potash-soda-felspars which have crystallized from granitic magmas under very high pressures should thus tend to have a lower soda-content than the normal, and show the orthoclase rather than the microcline form.

The occurrence of potash-soda porphyroblasts in xenoliths and similar metamorphosed rocks under conditions which preclude an origin by direct crystallization from a magma, raises the question as to how far it is justifiable to regard holocrystalline rocks, even of typical granitic appearance, as products of direct magmatic crystallization. The same process which gave rise to these porphyroblasts, if continued for longer periods or at elevated temperatures, might produce holocrystalline granitic rock structures without the mass having even approached the liquid state.

For such rocks the ordinary solidus-liquidus diagram would have no

meaning, but even under these conditions, crystallization of the potash-soda-feldspars would still conform to the exsolution curve, whose immiscibility gap would depend on the particular formation temperature. A consideration of the composition and degree of heterogeneity of the contained potash-soda-feldspars might provide useful information about the temperature and condition of formation.

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Correction to Part I (Min. Mag., 1937, vol. 24), p. 472, lines 2-3 from bottom: delete 'the results are set out in the lower curve of Fig. 18'.