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The Problem of Late-kinematic Granites

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Abstract

Among the granites the late-kinematic granites have the most pronounced intrusive character. All field evidence illustrates their magmatic origin. The mineralogy of the late-kinematic granites, however, and particularly of the mineral association microcline + albite, is inconsistent with such an origin and the fact that the potash feldspar of these granites is exclusively the low temperature form — microcline — seems to be contradictory to their formation from a molten magma as well.

After discussing this problem it is concluded that the late-kinematic granites were not emplaced in a molten state. Furthermore it is assumed that the intruded material (in solid state) may derive both from magmatic and metasomatic sources.

Contents

Introduction

The late-kinematic granites as defined by ESKOLA (1932) were emplaced in a late stage of orogeny. They usually cut the country rocks discordantly and behave as true intrusives. The chemical composition of these rocks is mostly granitic, approaching that one of the ideal granites of ESKOLA (1950).

The late-kinematic granites are rarely gneissose; they are medium- to fine-grained and tend to be aplitic, often they are pink and they readily form migmatites with older rocks. Such granites have many characteristics in common with the disharmonious granites of WALTON (1955), and they are identical with the ser-orogenic granites of WAHL (1936) and with the late-orogenic granites of SAKSELA (1936). The late-kinematic granites are probably also equivalent to most of READ's (1948) intrusive granites.

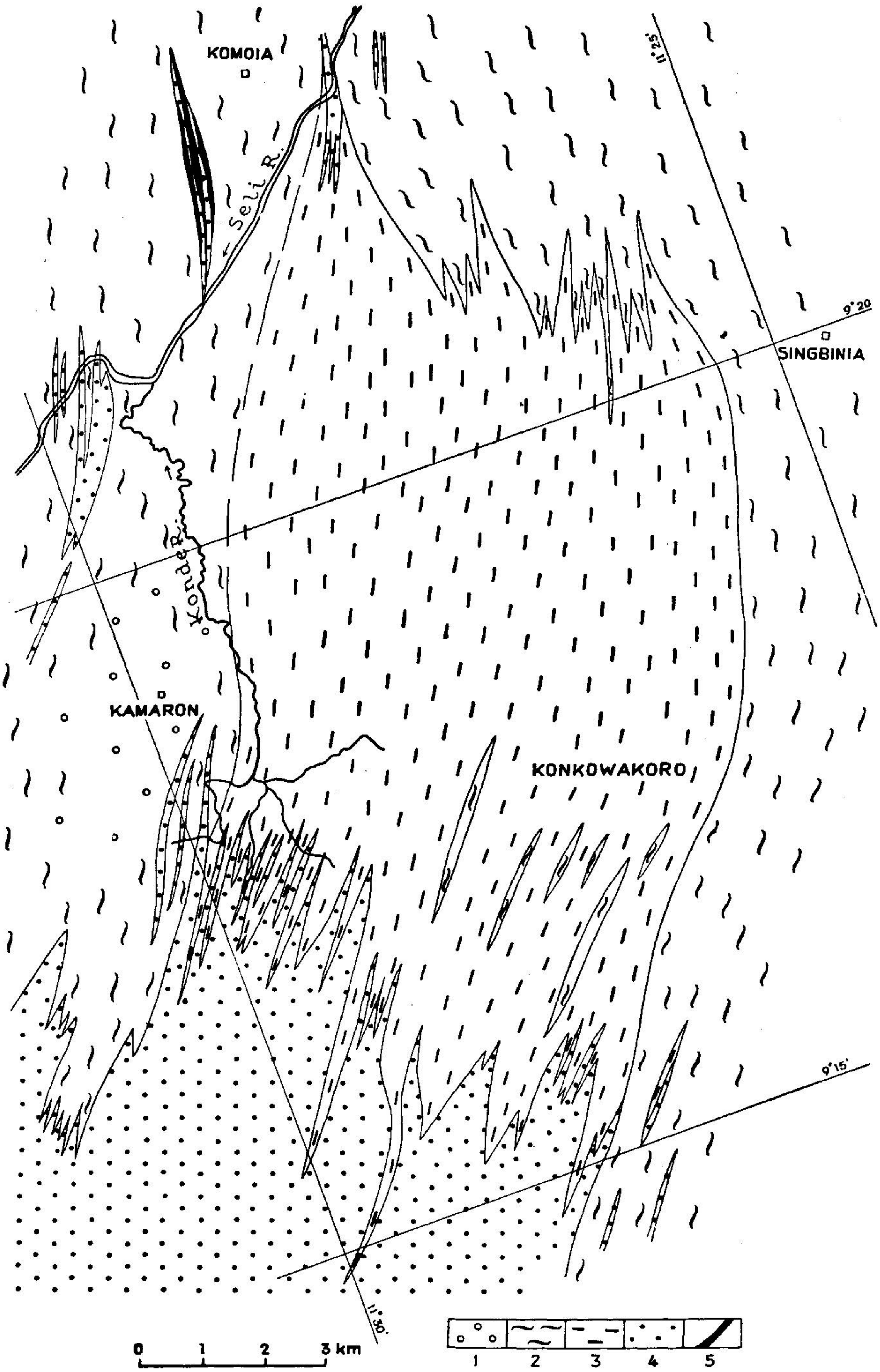
The present author has studied such granites in Central Sierra Leone, where they form 3 to 4 per cent of a Pre-Cambrian synkinematic area of 7500 km^2 mainly composed of granodiorites and gneisses; and he has seen also many occurrences in Central Finland. He has pointed out (MARMO, 1956a) that the late-kinematic granites are those the origin of which is really problematic. Concerning the synkinematic granites, the majority of petrologists are in agreement about the metasomatic origin of their potash feldspar component, which gave to the rock its granitic composition.

Late-Kinematic Granites

The bodies of late-kinematic granites greatly vary in size. These granites may form aplitic veinlets less than 1 inch in width, or they may form bosses and stocks or dykes several kilometres long and wide. In thin sections, the material of the narrowest veinlets often cannot be distinguished from that one of the huge late-kinematic dikes. In figures 1 to 4, some Pre-Cambrian late-kinematic bodies of late-kinematic granite from Central Sierra Leone are illustrated. Fig. 1 shows a late-kinematic boss more than 45 km^2 in size. This boss consists of muscovite-epidote-microcline-albite granite, which may contain small amounts of fluorite as well. The granite body of fig. 2 is composed of muscovite-biotite-microcline-albite granite containing molybdenite and fluorite. Epidote is in this granite either absent or occasional. At its ends it migmatizes the country rock, and it contains nebulous skialiths of extensively granitized foreign material. This granite occupies the crest of a gentle fold. Fig. 3 illustrates a large late-kinematic granite dyke, up to 750 m wide and approximately 15 km long which forms migmatite along its edges. In fig. 4, small granite veins are shown.

None of these occurrences possesses chilled margins, the presence of

Fig. 1. The late-kinematic granite boss at Kamaron, Central Sierra Leone. 1 = porphyroblastic granodiorite, 2 = granodiorite gneiss, 3 = late-kinematic granite, 4 = amphibolite, 5 = magnetite gneiss.


KOMOIA
Seli R.
Konde R.
KAMARON
KONKOWAKORO
SINGBINIA
11°25'
9°20
9°15'
11°30'
0 1 2 3 km
1 2 3 4 5

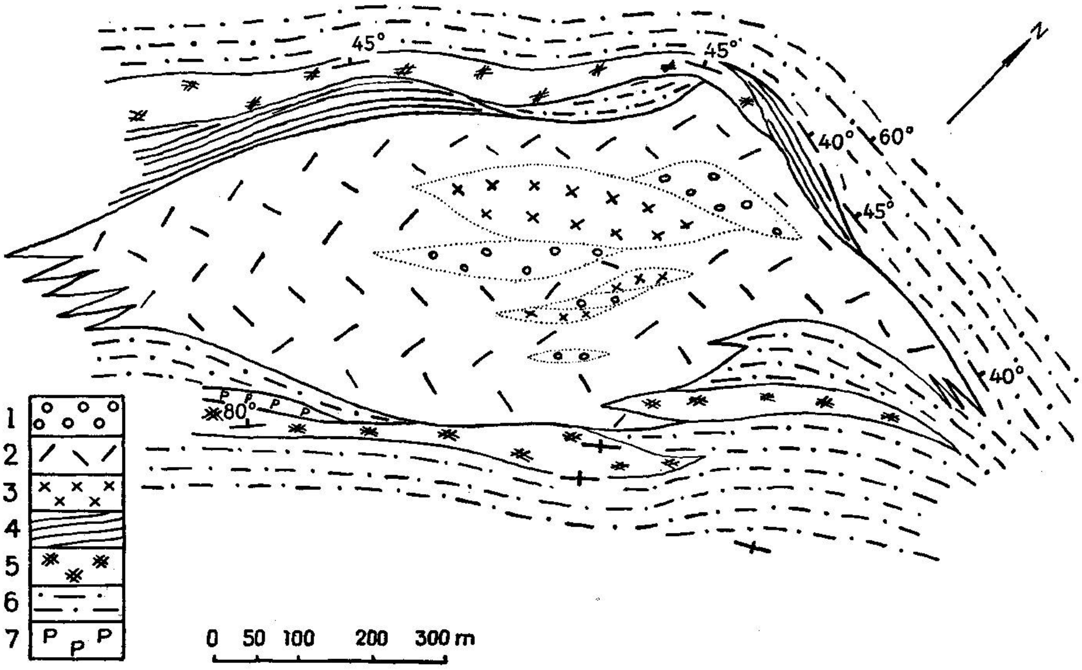


Fig. 2. Late-kinematic granite which intruded the crest of a gentle fold. Near Wankatane, Central Sierra Leone. 1 = skialiths of the porphyroblastic gneiss, 2 = late-kinematic granite, 3 = late-kinematic granite which contains molybdenite, 4 = acid volcanics, 5 = amphibolite, 6 = tremolite schist, 7 = pegmatite.

which is characteristic of many dolerite dykes and which would be expected if hot material had intruded into the cold environment. This proof against the magmatic origin of the late-kinematic granites, however, is only ostensible because, in the case of granite intrusions, the difference of temperature between the intruding material and the wall obviously cannot have been very great. Such intrusions took place in great depths of course and under conditions probably not very different from those of regional metamorphism.

Objections against the magmatic origin of these granites may be made on the basis of the experiments of Schairer and Bowen (1955, p. 742) who pointed out that "geologic evidence indicates that the rhyolites and obsidians which are the extrusive equivalents of granitic rock types were extruded as viscous flows or ejected as tuffs and pumices". The formation of narrow late-kinematic granite veinlets and of migmatites, however, indicates an entirely different behaviour or the „granitic magma". This objection may be overruled by the fact that the water content changes the behaviour of a melt of granite composition fundamentally, and Schairer and Bowen fully realized that water greatly reduces the

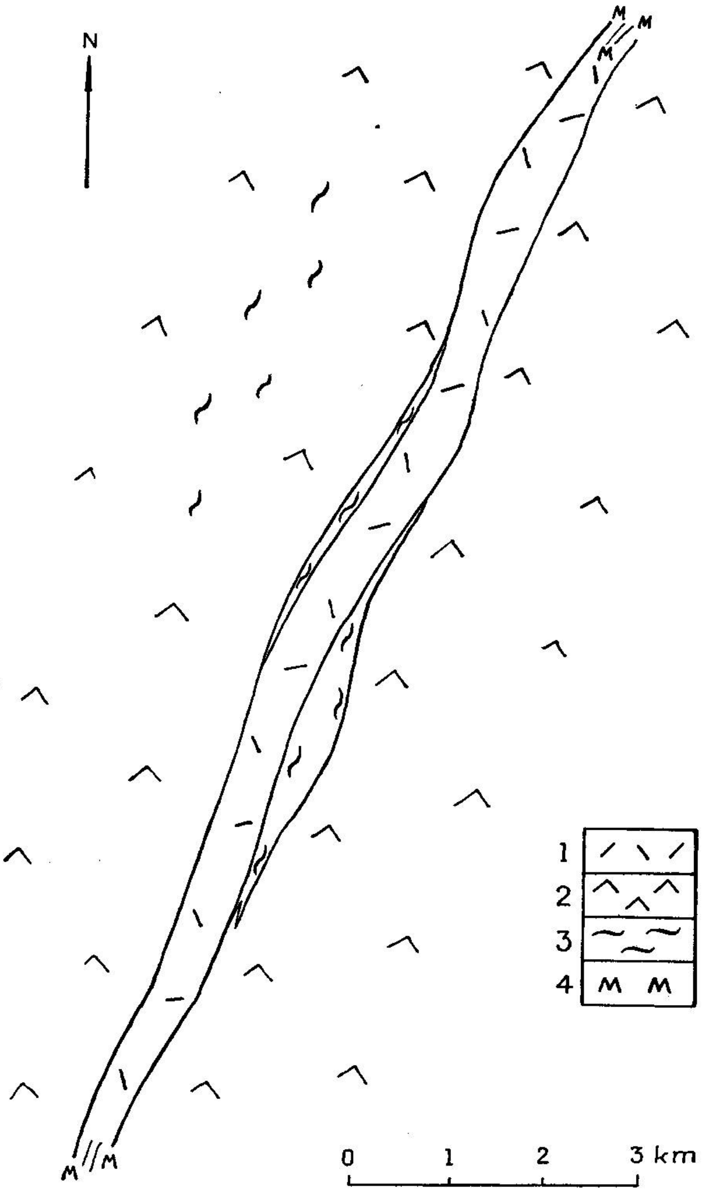


Fig. 3. Late-kinematic granite dike. Kurakoro, Central Sierra Leone. 1 = late-kinematic granite, 2 = granodiorite, 3 = granodiorite gneiss, 4 = migmatite.

viscosity of granite melts. SOSSMAN (1948) stated that 5% of water may fluidity it perfectly (actually such a granite mass would contain solid mineral particles "lubricated" with aqueous vapour).

Consequently, the field evidence is such that these granites may be considered as magmatic, and particularly so if the term "magmatic" does not necessarily mean an emplacement in perfectly molten state, but an emplacement of material derived from a molten material. Such an assumption is in keeping with the recent proposal of ESKOLA (1956),

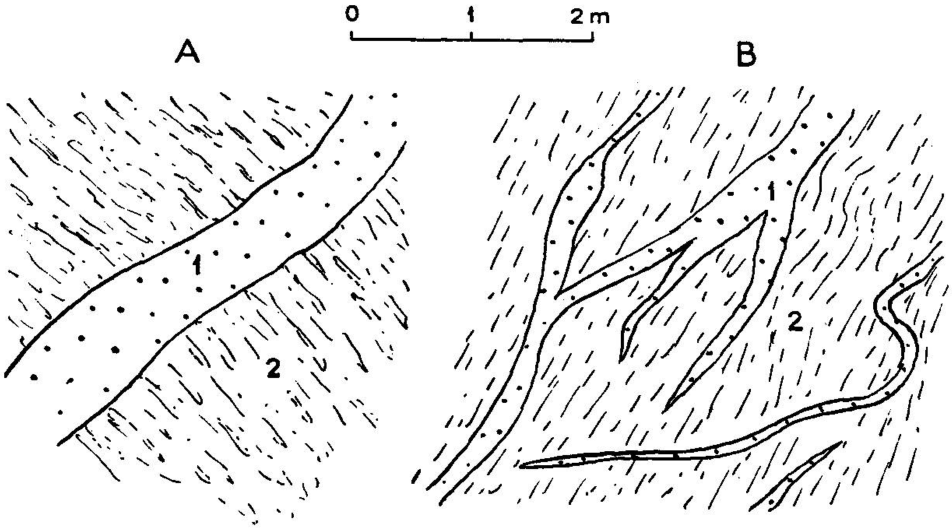


Fig. 4. Late-kinematic aplite veinlets. Kangari Hills, Sierra Leone. A: in amphibolite, B: in migmatite. 1 = aplite, 2 = amphibolite (in A) and mica gneiss (in B).

who now believes that the crystallization of the late-kinematic granites continued and actually took place after the magmatic stage in the evolution of granites.

It is the composition and texture of the late-kinematic granites which offer the most serious objections against the magmatic origin of these granites.

Composition of Late-kinematic Granites

The analyses of some late-kinematic albite-microcline granites, all originating from Sierra Leone, are presented in table 1. For comparison the analysis of a typical synkinematic granodiorite (VM 161) is included as well. From these analyses one can see, that the plagioclase of the Sierra Leone late-kinematic granites is typical albite with 2.2 to 16.9% *normative* An. According to the microscopy of these rocks, the actual anorthite content of plagioclases of most late-kinematic granites of Sierra Leone is 10% or less, and of all specimens examined less than 15%. In the synkinematic granites the plagioclase is characteristic oligoclase with more than 20% An (mostly An_{25-30}).

In many late-kinematic granites of Central Sierra Leone epidote may be present as well. In potassium-rich varieties, the amount of epidote is less than 2%, usually less than 1%. But there late-kinematic "granites" with Na > K occur in which the epidote-content is higher and exceptionally may rise up to 10% by volume. Rocks so rich in epidote are close to the helsinkites of LAITAKARI (1918) and they are granodiorites in

Table 1. *Chemical analyses of the late-kinematic granites of Central Sierra Leone*

	VM 10 R. Seli	VM 156 Kunya	VM 199 Kensekoro	VM 45 Tonkolili	Makong	M 161V Kurumanto (syn. granod.)
SiO_2	74.66	68.50	71.33	75.10	74.88	71.27
TiO_2	0.07	0.04	0.24	0.07	0.045	0.05
Al_2O_3	12.25	15.76	14.34	13.56	14.98	15.16
Fe_2O_3	1.70	1.92	2.16	0.43	0.26	1.75
FeO	0.54	0.70	0.43	0.12	0.40	0.87
MnO	0.19	0.09	0.13	0.65	0.22	0.10
MgO	0.31	0.60	0.34	0.32	0.04	0.58
CaO	1.12	1.98	0.69	0.70	0.90	2.76
Na_2O	3.35	4.54	4.08	3.22	4.88	4.82
K_2O	5.15	4.83	4.81	4.76	2.98	1.72
P_2O_5	0.01	0.50	0.48	0.13	0.06	0.26
H_2O+	0.66	0.46	0.61	0.51	0.46	0.48
H_2O-	0.07	0.13	0.38	0.03	0.05	0.05
Cl					0.01	
F		0.03	0.04			
Li_2O					trace	
NiO					trace	
Total	100.18	100.08	100.06	100.10	100.165	99.91
Sp. Grav.	2.64	2.66	2.61	2.65		2.66
An % in plagioclase	10.1	16.9	2.2	9.4	9.05	23.6
Number of cations per 160 anions	93.2	95.2	94.2	92.4	93.05	93.9
al	41	42.5	45	48	51.5	43.5
fm	13.5	13.5	13.5	11	4.5	14
c	7.5	9.5	4	4.5	5.5	14
alk	38.5	34.5	37.5	36.5	38.8	28.5
alk + c/al	1.12	1.035	0.92	0.85	0.85	0.98
K_2O:CaO	4.6	2.4	7	6.8	3.3	0.6
Normative:						
Quartz	33.51	20.22	28.21	37.33	33.48	30.15
Anorthite	3.19	7.78	0.78	2.84	4.09	12.79
Albite	28.30	38.25	34.32	27.25	41.13	40.87
K-feldspar	29.61	26.30	21.96	21.18	10.90	8.89
% Or of (Or + Ab)	51	40	39	43.5	21	18

Analyst for VM 10, 45, 156, 161, 199: H. J. Broughton.
Makong: taken from "Report of Min. and Geol. Surv. Dept. Sierra Leone, for years 1930—1931". Analyst unknown.

composition (RAMBERG classed them with granodiorites of albite-epidote facies). These rocks will not be dealt with in the present paper, which is concerned with potash-rich Pre-Cambrian late-kinematic rocks of true granite composition.

In the case of the analysed rocks (table 1) epidote may also occur. In VM 199 as much as 2.3% epidote may be present, but usually there are less than 2%. In VM 156, an epidote-content of 4 to 5% is common (exceptionally up to 8%). In VM 10 and in VM 45 the epidote is practically absent. At Makong it may be present in sheared portions only, but even then rather occasionally.

The writer thinks that the presence of epidote would not affect the *normative* composition of the rock, if it is a product of a later metamorphic alteration and if its formation is due to the anorthite component of the original plagioclase. Thus, if the composition of plagioclase is calculated from the chemical analyses the composition obtained would be the one of original plagioclase.

Such a calculation is made in table 1, and there it appears, that the original plagioclase of those granites was albitic (except VM 156, but even this plagioclase contains much more albite than do the synkinematic granitic rocks, so for instance VM 161).

Table 1 includes the Sierra Leone late-kinematic granites only; the tendency of plagioclase to be albitic in the late-kinematic granites has, however, been observed in the other parts of the world as well. WAHL (1936) gave as criterion for the petrochemistry of his syn- and serorogenic granites the ratio $K_2O:CaO$, which, for the former is less than 1, for his serorogenic granites more than 2, often more than 4. This is valid for the Sierra Leone granites as well, and in the analysed late-kinematic granites (table 1) the ratio is 2.4 to 7.

It is particularly noteworthy, that for the Pre-Cambrian late-kinematic granites of Central Sierra Leone the mineral assemblage albitic plagioclase + microcline + quartz is characteristic. Thereby, epidote may or may not be present. Another important point is that their potash feldspar is exclusively microcline.

Potash-Feldspar-Albite

The system $KAlSi_3O_8$-$NaAlSi_3O_8$-H_2O has been studied by BOWEN and TUTTLE (1950). The equilibrium diagram of this system is reproduced in fig. 5. According to this diagram, a mixture of 40 to 70 per cent of potash-feldspar and the rest of albite yields a single feldspar above

660° C. The single K-Na-feldspar becomes unstable and breaks up into two phases, into potash-feldspar + albite, if heated for a prolonged period below solvus temperature. Consequently, under magmatic conditions, the crystallization of potash-feldspar together with albite in separated grains is most improbable.

From the analyses of table 1 one can see that in the late-kinematic granites of Central Sierra Leone such hypothetical single K-Na-feldspar (if primarily formed as such) would have contained 39 to 51% potash feldspar in most cases. According to the study of the modal composition of late-kinematic granites, if taking the plagioclase as containing, on the average, 10% An, such hypothetical single feldspar would have contained 35 to 50% potash-feldspar. The varieties rich in epidote (mainly albite-epidote granodiorite) would have contained in the single feldspar component less than 15% potash feldspar.

Further information about the microcline-albite relations can be obtained from table 2, which contains some analytical values of the late-kinematic granites of Finland and New Foundland. These samples are typical late-kinematic granites, and they all contain albitic plagioclase and but occasionally epidote. Furthermore, their potash feldspar is always microcline and the presence of perthite is unusual. If also in these granites a single K-Na-feldspar had existed, it should have contained 50 to 54% of potash-feldspar, with the exception of analyses (5) and (6) with 83 and 73% K-feldspar respectively.

In this connection it may be of interest to note, that according to SEDERHOLM (1925), the post-Bothnian granites of southern Finland on the average contain 1.51% CaO, 3.09% Na_2O, and 5.13% K_2O, and that

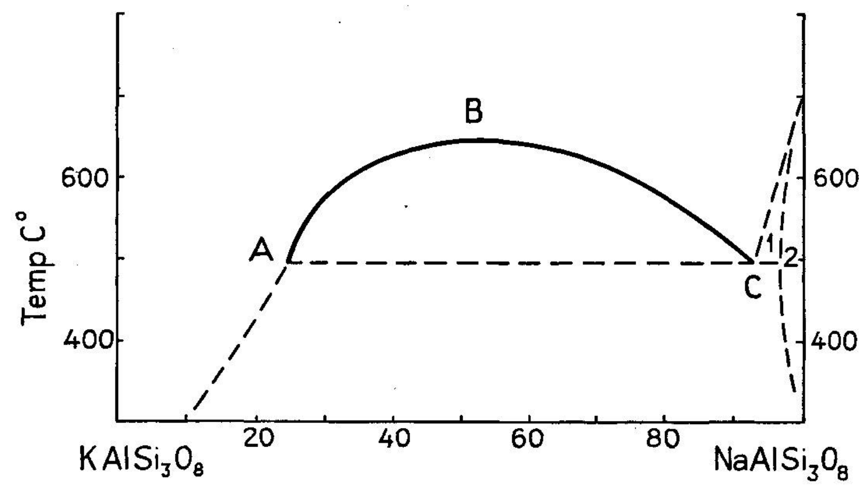


Fig. 5. Equilibrium diagram according to BOWEN and TUTTLE (1950).

their plagioclase is albitic. His Post-Kalevian granites contain an average of 1.81% CaO; 3.04% Na_2O, and 4.98% K_2O. In the rapakivi granites, the corresponding values are 1.34, 2.30, and 6.10%.

Among the Finnish late-kinematic granites, those of Nattanen and Hanko are taken by ESKOLA (1956) as representing his ideal granites, and they contain resp.: 1.00 and 1.59% CaO, 2.42 and 2.25% Na_2O, and 6.53 and 5.85% K_2O. On the basis of all these analyses it seems that the conclusions drawn from the late-kinematic granites of Sierra Leone regarding the ratio microcline to albite and the composition of plagioclase are reliable also for some kind of generalization.

TUTTLE (1952) stressed that the co-occurrence of potash feldspar and albite in the granitic rocks is inconsistent with their magmatic origin. To explain this inconsistency, TUTTLE started from the assumption that in the slow-cooling plutonic rocks a prolonged heating is expected and this would cause there the unmixing of the primarily single Ka-Na-feldspar. On the basis of his study of perthites, and due to the occurrence of secondary albite along the grain boundaries between potash feldspar and plagioclase, he concluded that then exsolution virtually may reach

Table 2. *Alkali contents and composition of feldspars of some late-kinematic granites.*

	1	2	3	4	5	6
CaO	0.52	1.63	0.84	0.18	0.54	0.45
Na_2O	4.51	2.83	3.02	0.68	1.92	3.90
K_2O	5.97	5.93	4.29	4.55	6.43	4.54
Plagioclase	39.9	29.9	29.8	5.76	13.5	29.5
Microcline	35.0	30.6	27.1	27.0	40.7	31.8
Epidote	0.4	—	—	—	—	—
% K-feldspar in the hypothetical single K-Na-feldspar	50.0	54.0	50.0	83.0	73.0	52.0

1 = Microcline granite, W shore of the Lake Katumajärvi, Finland (SIMONEN, 1948, p. 24).
2 = Microcline granite, between Alajärvi and Hattelmajärvi, Finland (SIMONEN, 1948, p. 24).
3 = Reddish migmatic granite, Hopeavuori, Pernaja, Finland (VAASJOKI, 1953, p. 41).
4 = Molybdenite aplite, Säynätsalo, Finland (KULONPALO and MARMO, 1955, p. 40).
5 = Molybdenite aplite. Ackley City, New Foundland (cited by KULONPALO and MARMO, 1955, p. 40).
6 = Normal aplite. Rencontre Lake, New Foundland (cited by KULONPALO and MARMO, 1955, p. 40).

such a stage that separate grains of both feldspars will result. Accordingly, TUTTLE puts forward the criterion for the magmatic and metasomatic granites (TUTTLE, 1952, p. 113): "If, ..., it can be demonstrated that salic plutonic rocks containing relatively pure potash feldspar and soda feldspar have not formed by unmixing, then a useful criterion for an origin other than magmatic is indicated, ..." According to TUTTLE the two-feldspar-composition of the granites containing perthitic potash feldspar is most probably due to unmixing as defined above.

The late-kinematic granites of table 1 have such a plagioclase, the anorthite content of which is far too small to result from the crystallization of two feldspars from a trachytic magma, because then, according to TUTTLE, the composition should be about An_{25-40}. Regarding the granites of table 2 the amount of potash-feldspar is still higher, and, according to the diagram of fig. 5, the solvus temperature is still lower. In extreme cases with less than 20% albite, the solvus would drop to about 500° C. Furthermore, x-ray investigation revealed that the microcline of the granites of Sierra Leone contain but very little sodium. Perthite is rather occasional in these granites.

From such granites it may be inferred that there the two kinds of feldspar cannot have formed from a magma. They must have originated in some other than magmatic way, because — as will be shown later on — an unmixing is very improbable as well.

Of course, this deduction may not be entirely dependable because the system orthoclase — albite — anorthite — water still remains to be investigated and thus the role of calcium in the equilibrium conditions of orthoclase — albite — water is not sufficiently known. But, however, the available published informations seem to support this conclusion.

So far, only granites have been kept in mind which do not generally contain perthite. But late-kinematic granites containing perthitic potash-feldspar are also known. In Central Sierra Leone, such granites are uncommon. But there a syenitic granite occurs which is also late-kinematic and exceptionally rich in perthite. Its plagioclase, however, is not albite but contains more than 35% anorthite. This "granite" being rather syenite than granite and obviously belonging to a different category than the albite granites discussed in this paper, we shall not speak of it here. Elsewhere, however, perthite may in some cases be comparatively common with the albitic late-kinematic granites as well. Thus also the question if perthite be a proof of magmatic origin or not is here of importance and especially so, because the answer will make it clear whether an unmixing can proceed beyond the perthite stage or not. This question, however, is linked with the fact that in late-kinematic granites microcline is the form of potash-feldspar occurring, not orthoclase.

Microcline and Orthoclase

The potash-feldspar of the salic plutonic rocks of Central Sierra Leone is exclusively microcline, which is the low-temperature form of potash-feldspar (Laves, 1952; Tuttle, 1952; Goldsmith and Laves, 1954). At 700° C it converts into orthoclase, but under hydrothermal conditions the triclinic microcline may change into the monoclinic modification already at 525° C (Goldsmith and Laves, 1954). Microcline has never been synthesized. Laves (1951), however, has reported microcline as the product of an experimental potassium metasomatism of albite. Wyart and Sabatier (1954) succeeded in producing microcline by replacing albite by potash-feldspar under hydrothermal conditions.

Regarding the formation of microcline in rocks, two schools exist. One of them explains the origin of microcline as being due to the ageing or recrystallization of orthoclase, while the other one states that the microcline may also grow directly. Laves (1950, 1955) supports the view that microcline (which is cross-hatched) is the product of a re-arrangement of the monoclinic crystal. He based his opinion on the crystallographic facts (Laves, 1955): "If microcline appears cross-hatched in such a way that the twin plane of those lamellae which follow the albite law is perpendicular to the twin axis of those lamellae which follow the pericline law, such microcline has previously been a monoclinic potash-feldspar modification (sanidine)." Marmo (1955c), however, proposed a small modification to this assumption, supposing that this monoclinic ancestry may appear at a very early stage of the formation of microcline and that microcline may practically grow in triclinic form despite the presence of cross-hatching. Such a possibility is well consistent with the arguments of Laves.

There are, however, many instances for the formation of microcline as a result of the re-arrangement of the Al-Si framework of an orthoclase. Eskola (1952) described such a transformation in the orthoclase-bearing granulites of Finnish Lapland and many other authors do so of other orthoclase-bearing rocks and particularly of the rapakivi granites of Finland. Such a transformation, however, is rather unlikely in ordinary synkinematic granites or in late-kinematic rocks which exclusively contain microcline of the highest triclinicity (see Marmo, 1955c). For such cases, the writer has proposed the explanation that the formation of microcline is due to a slow enough accumulation of material taking place under such conditions that the temperature of formation is definitely below that one of the transformation of the triclinic modification into the monoclinic one. Such conditions must be expected in synkinematic granitization, and particularly so if microcline is replacing plagioclase.

Consequently, for the microcline two different origins must be accepted, or, rather, two modifications of one similar origin:

1. In the orthoclase-bearing rocks (including most of the post-kinematic granites of the Alpine chains) the orthoclase will be formed if the potash-feldspar is developing at a temperature below the temperature of transformation but from material accumulating more rapid than the re-arrangement of the monoclinic lattice into a triclinic one can take place (a process which, according to LAVES, is a very sluggish one). This modification, however, tends to re-arrange itself into the triclinic, but, as is revealed by the study of granulites, rapakivi-granites, or Alpine post-kinematic granites, this transformation is very seldom, if ever, complete.

2. In the synkinematic granites, the temperature during the formation of potash-feldspar is probably well below that one of the transformation. During the potassium metasomatism or granitization the growth of the potash-feldspar obviously takes place very sluggishly. If the rate of the accumulation of material is below that one of the transformation, the triclinic microcline will be formed directly (even if, in the initial stage of the formation it is of monoclinic symmetry).

One may ask whether in the plutonic rocks the transformation of orthoclase into microcline could possibly be complete to such an extent that no monoclinic modification is left. Theoretically such a possibility exists. In practice, however, it cannot be as common as it should if all the microcline of the synkinematic rocks had been formed in such a way. One must remember that both the transformation from monoclinic into triclinic modification and the introduction of potassium in synkinematic rocks are taking place extremely sluggishly. In the rapakivi granites all intermediates between monoclinic and triclinic potash-feldspar exist (oral communication by Dr. K. NEUVONEN), proving the transformation of orthoclase into microcline. In granulitic rocks where such a transformation took place (ESKOLA, 1952) orthoclase is still and always present as well and in different crystals of the same specimen the "microclinization" reached different degrees. There may be grains almost entirely transformed into microcline while others show only a faint beginning of such a transformation. And yet, before attaining their present condition, these granulites certainly passed through conditions very suitable for such a transformation, and they very probably remained there long enough to have their orthoclase completely transformed into microcline, if in ordinary synkinematic granites the latter should have developed from a monoclinic form due to the re-arrangement of the lattice exclusively. It is also important to note that the aplite veinlets cutting these granulite granites exclusively contain highly triclinic microcline, but no orthoclase. This proves that the potash feldspar of aplite primarily crystallized as microcline.

A similar relationship between orthoclase and microcline has been described by GYSIN (1948, 1956) for young granites from the Alps and from the Himalaya in which, consequently, the microcline is derived from orthoclase; in younger aplite, however, microcline is primary there as well. Microcline, if primary, could not have crystallized under magmatic conditions (compare p. 30).

Microcline and Perthite

There seems to be a close connection between the modifications of potash-feldspar and the perthite. According to TUTTLE (1952, p. 114) the series: sanidine — sub-X-ray perthite — X-ray perthite — cryptoperthite — microperthite — perthite represents a decreasing temperature and an ascending time scale. LAVES (1952) suggests that the solvus temperature of any perthite is about the temperature of transformation from monoclinic to triclinic.

In good agreement with the TUTTLE's series is the finding (ESKOLA, 1952) that in the orthoclase-bearing Lapland granulites of Finland, only thin lamellae of a "hair-perthite" occur, but in the synkinematic granites (without orthoclase), microperthite is the usual, as it is also in the perthite-bearing late-kinematic granites.

Using X-ray methods, LAVES found that all cryptoperthites (sub-X-ray and X-ray perthites of TUTTLE) actually are quasi-homogeneous perthites (OFTEDAHL, 1948), which (LAVES, 1952, p. 563): "are not two distinct phases but represent, instead, an assemblage of areas having compositions approaching those values given by the appropriate exsolution curve. They are, in a sense, solid solutions with compositional fluctuations that considerably exceed those found in a normal mix-crystal. There are no distinct boundaries between the areas of differing composition."

These quasi-homogeneous perthites in fact demonstrate the "recrystallization" of the feldspars of the granitic rocks which obviously leads towards the re-arrangement of the Al-Si framework corresponding to a lower free energy. For that reason, at higher temperatures (but still below the solvus) the exsolution (through diffusion in solids) of albite, and the transformation of monoclinic potash feldspar into triclinic microcline are parallel features.

If the formation of potash-feldspar takes place at a sufficiently low temperature, and the accumulation of materials is sufficiently sluggish, it is reasonable to assume, that no perthite can be formed but, instead, a mosaic of albite and microcline.

On the other hand, if the formation of potash-feldspar is accompanied by a somewhat elevated temperature and is less sluggish, it is expected that orthoclase would be produced instead of microcline, and thereby perthite would be produced as well. If the accumulation of materials at a somewhat elevated temperature is very sluggish, the kind of perthite occurring in microcline may develop.

If the mechanics leading to the formation of perthite is that of exsolution, it would take place due to a diffusion through solids. It is then well expected, that the trend to this exsolution would continue until as pure and well ordered a potash feldspar is produced as possible. After that, there will not necessarily be any need of forcing the exsolved albite out from the microcline crystal. At this stage, there obviously exists an equilibrium within the perthitic microcline crystal between the ion concentrations of Na and K (at the margins of the coarse perthite spindles), for otherwise the feldspars would replace each other. The replacement would proceed in the direction of a prevailing concentration of Na or K, exactly according to the experimental findings of O'Neill (1948). Thus, there are no reasons why the exsolution should continue beyond the stage of a coarse perthite and produce separate grains of albite and microcline. It is to be noted that in all orthoclase-granites seen by the present writer potash-feldspar was always strongly perthitic.

Marmo and Mikkola (1955) have shown that there are in the granitic rocks of Central Sierra Leone two groups of microcline differing in the amount of 2 V. In the pegmatites and in the porphyroblasts of the porphyroblastic granites (not seldom perthitic in both cases) the 2 V amounts to 76—78°. In the interstitial microcline and in the microcline replacing plagioclase 2 V amounts to 84 to 86°. The values between 78 and 84° are rather occasional. Consequently, there does not appear any continuous series in the amounts of 2 V, as it would be expected if microcline had formed from orthoclase. It is interesting to see, that also the microcline of the late-kinematic granites (non-perthitic) has a 2 V = 84°. According to SPENCER (1937) the amount of 2 V is decreasing under the influence of prolonged heating. Hence one may assume that the larger 2 V indicates a lower temperature of formation. This conclusion is in agreement with the finding that perthitic potash-feldspar may have formed at a somewhat higher temperature than the non-perthitic one (p. 33). The difference in 2 V, on the other hand, means a different rate of growth as well.

According to the theories presented above, the formation of perthite due to exsolution is expected if the formation of potash-feldspar has taken place at a somewhat elevated temperature. That does not mean, however, that this temperature need be above the solvus, hence, that the change took place under magmatic conditions.

Perthite may occur also in an environment where its formation at an elevated temperature is not likely; it is comparatively common in porphyroblastic granites. The writer has seen perfectly microperthitic microcline porphyroblasts growing across the fractures of a rock, and he has also found similar porphyroblasts in a matrix of amphibolite and of quartzite. RAMBERG (1952) explained the formation of such porphyroblasts with their concretionary growth. This explanation is in full agreement with the results the writer deduced from the study of the porphyroblastic granites of Central Sierra Leone (MARMO, 1956b). The concretionary growth is undoubtedly a very sluggish process, the temperature must have been below the solvus of albite – microcline, and the conditions of such a growth could well establish an environment which is suitable for the direct formation of microcline. Obvisously, in such cases the formation of perthite in primarily formed microcline is due to a sluggish accumulation of materials and a growth side by side with porphyroblasts.

HEIER (1955) has discussed the perthites of Norwegian metasomatic augen-gneisses. On an analytical basis he found the composition of these perthites to be $Or_{68.9}Ab_{30}An_{1.1}$, and ascertained that the K-feldspar of these perthites is pure. HEIER's interpretation of perthites exactly opposes that one of TUTTLE (HEIER, 1955, p. 90): "The presence of such perthites in a metasomatic rock suggests a formation by replacement and not by exsolution", and "it is concluded that, in this area, the mesoperthite represents an intermediate stage in the complete replacement of plagioclase by potash-feldspar."

HÄRME (1954) has described porphyroblasts with perthite up to 3—4 cm across which have a plagioclase rim (An_{23-25}). The microcline forms there minute spots, which form a rim parallel to the contours of the crystal. Both these spots and the perthite spindles have an extinction parallel with the enveloping plagioclase rim and in some places the perthitic spindles begin at the plagioclase rim. This case supports the view of HEIER well.

The writer, however, does not fully agree with the replacement theory, because he has seen and described replacement features of plagioclase by microcline, but they yield an entirely different pattern that is represented by perthites (MARMO, 1955b). In his opinion, the theory proposed by HEALD (1950) is much more promising (p. 88): "The lamellar feldspars (perthite) which have large axial angles may be examples of anomalous mixed crystals (see SEIFERT, 1935 and 1936). These intergrowths are formed by simultaneous intercrystallization of two phases, one being disseminated in oriented fashion in the host crystal as a sort of buried intergrowth."

During the slow growth of feldspar, if both sodium and potassium are simultaneously introduced, the formation of perthite in that way is virtually to be expected and in good agreement with the facts obtained in the field.

It has been concluded (p. 31) that the microcline of non-perthitic late-kinematic granites grew as microcline and, consequently, such rocks cannot have formed under magmatic conditions.

Regarding the late-kinematic microcline granites containing perthitic microcline, there still remains the possibility that they were formed above the solvus of the system orthoclase + albite + water, and that their potash feldspar was primarily monoclinic. This possibility is, however, much reduced by the fact that orthoclase is completely absent in such rocks. Thus probably the potash-feldspar grew triclinic there too and therefore also such late-kinematic granites which contain perthitic *microcline* and albitic plagioclase are of non-magmatic origin as far as their granitic composition is concerned.

The Emplacement of Late-kinematic Granites

As is revealed by field evidence, the late-kinematic granites considered in this paper are obviously intrusive. From this point of view they could be magmatic. Their chemical composition is consistent with that one of the hypothetical granite magma derived from a parent magma through differentiation. The mineral composition of the late-kinematic granites, however, is not consistent with the magmatic origin.

The perthite-bearing late-kinematic microcline-granite could be magmatic if: 1. it can be proved that in all cases the microcline was formed owing to the re-arrangement of the Al-Si framework of an orthoclase; 2. the formation of albite and microcline can be proved as being due to the complete exsolution of a single K-Na feldspar through the perthite stage or it is due to co-crystallization of both feldspars under magmatic conditions.

Regarding the monoclinic ancestry of the potash-feldspar of true microcline granites an actual proof against such a possibility could not be found, but it was shown that such a formation is unlikely.

Several strong arguments stand against the exsolution hypothesis of Tuttle (see p. 29). There are no intermediate stages between perthite and the mosaic of microcline + albite. Furthermore, it is difficult to understand why the exsolved albite (in perthites) should be forced out from a mix-crystal, because the advance of an exsolution in perthite appears as the thickening of the albite lamellae only. The appearance of perthite in undoubtedly metasomatic environment (p. 34) also suggests that the magmatic origin is in no way the only possible one for the formation of perthites. The study of the potash-soda feldspars suggests that the recrystallization of a granite would appear rather in a re-arrangement of the Al-Si framework of feldspars and in the formation of perthite, than in a transport of its materials beyond the recrystallizing crystals.

There is also a strong evidence indicating that microcline-perthite may be formed without a monoclinic intermediate stage (p. 34).

For that reason the writer is very much inclined to doubt that the late-kinematic microcline-granites containing albite and no orthoclase were emplaced in a molton state, despite their undoubtedly intrusive character, which has been recorded by many transformists as well (e. g. Read, 1948, 1952), but has been categorically repelled by others (Perrin and Roubault, 1950).

The conclusion that the emplacement of the late-kinematic granites could not take place in a molten state, does not necessarily contradict their intrusive character.

Mechanics suitable to mobilize any material without fusion do exist. The rocks may be mobilized in a plastic state, but their mobility may also be considerably increased by the addition of suitable fluxes, of intergranular fluids, most conveniently of water. According to Sossman (1948), an amount of 5% water can perfectly fluidity a mass of, say, granite composition. That is, the water which in the late-kinematic granites plays an important role, as may be assumed from the hydrothermal activities which often accompany the intrusions of the late-kinematic granites: quartz pegmatites have frequently been met with together with the late-kinematic granites, and in many occasions they bear a close relationship to the hydrothermal mineralizations. Molybdenite, galena, and bismuthite have often been found either in the late-kinematic granite or in related aplites and pegmatites.

Thus the writer believes that the intrusion of late-kinematic granites took place in a "solid" state but was mobilized by a sufficient amount of water. At this stage the materials probably moved in molecules and ions and their introduction (= emplacement of granite) was slow enough to establish appropriate conditions for the growth of microcline instead of orthoclase, and accordingly the temperature of the slow intrusion must have been below that one at which microcline will be re-arranged into orthoclase.

If the introduction of materials had been more rapid, orthoclase-bearing perthitic granites would have been produced.

Even if an agreement can be reached with regard to the manner of intrusion of the late-kinematic granites, an important question there still remains unanswered, the question: which material was intruded?

A Little Philosophic Geology

If, in the very remote past, the earth once was molten, at that time gravitative and fractional crystal differentiation undoubtedly largely operated. Under such conditions, the sial must have obtained large amounts of alkalies and silica from the interior of the molten globe. All potassium of primary sial was and is undoubtedly of truly magmatic origin in the strictest meaning of the word.

A very long time must have elapsed before the erosion could become really effective on the consolidated surface, and before the very first sediments could deposit.

We do not know anything about these primeval sediments. About their composition, however, we may guess something. Certainly they must have been very badly sorted out.

The recent sediments, especially the clayey ones, on the average contain much more potassium proportionally than do the average igneous rocks. They also are richer in potassium than the granodiorites supposed to have been formed from these sediments. Thus there seems to be good reason to assume that the potassium is enriched in sediments. Consequently, also the very first sediments of the globe were somewhat richer in potassium than the magmatic rocks, the disintegration of which produced the primeval sediments. Hence the potassium of the first sediments was of magmatic origin.

By the gradual accumulation of sediments such conditions were established under which the very first geosyncline could start its folding. From this stage, in the granite petrological sense the actualistic principle started to work — yet, however, not with its full capacity.

How this very first geosyncline was built up? In the main principles, this primeval geosyncline probably was similar to that, say, of the Alps. It differed from the latter essentially in the fact that most, if not all, of its sediments were derived from the virgin sial; and this was not as yet contaminated by any "sedimentogeneous" components. The sediments of this geosyncline had a splendid ancestry: they were immediate descendants of truly magmatic rocks. They were enriched in potassium, alumina, and silica which also had derived directly from the magma.

In recent days, granodiorite composes the majority of the synkinematic areas. It has been possible to demonstrate that if granodiorite derives from sediments it is richer or as rich in sodium as are the sediments, but it distinctly contains less potassium. On the other hand, granodiorite may contain portions of granite composition which may be even richer in potassium than are most potassic sediments. The potash feldspar of such rocks is always interstitial and definitely younger than other constituents of this rock. This evidence, together with textural and structural features, led the geologists to explain such rocks as products of granitization.

In the sense of Engel and Engel (1952) the present writer has suggested the working of such mechanics that in the geosynclinal orogenic conditions the compressed sediments undergo a "granodioritization" (Marmo, 1954) thereby losing some of their potassium and silica. These elements migrate towards the less compressed areas and re-appear in the shattered zones, in crests of folds, in large faults, etc., and there they cause "granitization".

Hietanen (Hietanen-Makela, 1953) assumed for the potassium a general trend to concentrate in upper parts of the sial. Thus, wherever a potassium molecule occurs within the globe, it has a tendency to migrate upwards. This view was also expressed by Eskola (1956) in his last account on the granite problem.

The potassium ion, when moving upwards (or towards spots of the lower free energy) may use any means of propagation. In the most difficult circumstances the potassium must even accept the most tedious means of transportation so, for instance, the diffusion through solids. If possible, it follows the easiest ways available, as there are the intergranular films, pore solutions, etc. All these factors help to build up an accumulation of potassium (and silica) in favourable places.

If such an accumulation reaches sufficiently large dimensions, it may disturb the isostatic equilibrium and appear in doming. These accumulations may also be mobilized by the interstitial fluids (water) and then intrude faults, fractures, fold crests, and any opened or easily opening places.

In the primeval geosyncline, the granodioritization and granitization obviously operated as well. At that time, however, these processes necessarily were of much less importance than in later geosynclines, because the sediments of the first geosyncline were badly sorted, and they could not have been as rich in potassium as are the sediments of later geosynclines. Therefore one must assume additional sources for potassium in this geosyncline. Obviously this additional potassium was brought up, again, from the juvenile sources. These sources probably represented the granite magma itself, the last product of the differentiation of the whole globe. There are no reasons why the presence of this granite magma should be forbidden to later geosynclines. There may be one reason: the thickening of the sial. This argument was partly refused by BUDDINGTON (1948) who assumed that the granite magma derived palingenetically from this sial.

The experiments of KRANCK and MCQUAIG (1953) have shown that in natural rocks biotite will melt first, before the salic constituents. Thus their experiments rather explain the formation of diabase than aplite dikes. On the other hand, under hydrothermal conditions this melting may proceed otherwise (personal communication by YODER) and, in any case, at the depths of the proper sial the melting points of all rock-forming silicates may be attained at least sporadically, and there the refused sial may be differentiated to produce granitic residual "magma" (richer, however, in lime than are the late-kinematic granites discussed above).

This differentiation may also mean a simple release of alkalies, alumina, and silica which all probably tend to reach the same loci as the elements escaping from the sediments subjected to granodioritization. Consequently, there the mixing of elements derived both from the sial and from the sediments takes place. That explains the appearence of really large granite bodies of undoubtedly intrusive character the existence of which cannot be explained merely on the basis of materials derived from sediments.

Unfortunately, there are no facts available for the mutual relationship of the rates of migration of K — Na — Si — Al. Maybe this ratio is just appropriate for an accumulation of material of granite composition. If this ratio is markedly different from that necessary to establish the granite composition, the formation of the late-kinematic granites must predominantly be attributed to the supply of materials from the sial. The composition of minor aplite veins, however, strongly suggests that the migration rate of alkalies and silica tends to be such that during a sluggish accumulation a composition not too far from that of ideal granite will be attained. The idea of fractionation of ions due to different speed of migration was proposed already by TUOMINEN and MIKKOLA (1950) for the mechanism of magnesium metasomatism. The history of granites outlined above, includes the assumption that, to some extent at least, the granites begin as a melt of the deep interiors of the syncline, but that their material did not melt at the stage of the intrusion, as has been deduced from the available facts.

Thus, in the sense of the hypothesis given above, the magmatic view is strictly correct at the stage of the intrusions preparing (materials derived from the granodioritization process excluded). But while the intrusions are taking place, the transformistic views can better explain the field observations. In the opinion of the writer the material of the intrusions derived both from magmatic and metasomatic sources.

It is worth noting, that with more advanced erosion the late-kinematic granites would obviously increase on the surface if they were related to the deep-seated magma-reservoirs (which, according to BARTH, 1952, are occasional). In the studied areas, however, this is not the case, but in the oldest Pre-Cambrian areas (West Africa) the late-kinematic granites are less abundant than in Finland, where, according to radiogenic age determinations, the Pre-Cambrian is probably almost 10^9 years younger than in West Africa. In the Adirondacks of America which are younger still, the amount of late-kinematic granites is proportionally increasing, and in the Atlas of Morocco the late-kinematic granites very much exceed the undoubtedly metasomatic salic plutonic rocks. This, of course, is not without marked exceptions.

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