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On granites; a revised study

by Vladi Marmo

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ON GRANITES
A REVISED STUDY

BY

VLADI MARMO

WITH 24 FIGURES IN TEXT

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ABSTRACT

The paper is a review of the granite problem, in which basically the classification of Pentti Eskola into syn-, late-, and postkinematic granites is adopted. Petrological features as well as mineralogical characteristics have been emphasized and their significance pointed out where genetical interpretations are concerned. Taking also into account the results of experimental petrology and mineralogy, conclusions are drawn which favour metasomatic origin for microcline granites rather than origin from a melt. For orthoclase-bearing granites and such microcline granites which contain strongly perthitic microcline, crystallization from a water-bearing melt seems possible.

The sedimentary rocks themselves are taken as the most important source of potassium, and many features of granitization are explained in opposite direction: as results of the extraction rather than of the introduction of potassium.

A petrographical classification of granites is also proposed.

Helsinki 1967. Valtion painatuskeskus

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INTRODUCTION

According to the definition given by Johannsen (1941, p. 124), granite is »characterized by quartz forming more than 5 and less than 50 per cent of the quarfeloids, and by feldspar ratio such that Kf forms from 95 to 50 per cent of the total feldspar contents. The plagioclase is CaNaF, and the mafites form more than 5 and less than 50 per cent of the total constituents.»

This definition (of granite) is close to those accepted by many other authors. In common use, however, the word granite has often meant any granular plutonic rock containing quartz and feldspars. To this Walton (1955) objected vigorously, and, in the opinion of the present writer (Marmo, 1956a), with full justice, since, due to this designation, many rocks have come to be included in the »granites» which have nothing to do with granite in the petrological meaning of the term. This is probably one of the most serious reasons why opinions regarding both the emplacement and the origin of granite are so many and so controversial, because despite such a generalization, when the origin of granites is discussed, still the experimental work done on true granitic composition is usually taken as the basis of such a discussion.

Any modern treatise on granites, however, should and does restrict itself to actual granites of respective composition, which still often deviates from that proposed by Johannsen. So, for instance, Tuttle and Bowen (1958) propose to call such rocks granites or rhyolites, whenever the texture and environment may require, which contain 80 per cent or more of the normative constituents, albite + orthoclase + quartz, and which occupy the central part of the Ab — Or — Q triangle.

It is remarkable, that if the rocks fulfilling the above-mentioned requirement are inserted in this triangle, there appears a very distinct maximum at about one-third albite + one-third ortoclase + one-third quartz.

Within the same range, but still distinctly deviating from the last-mentioned maximum, falls also the »ideal granite» of Eskola (1950).

When considering international literature on granites, it can be noted, that the majority of papers discussing granites and their origin are, in actual fact, not concerned with granites at all. There are some authors who group almost all the acid plutonic rocks under this term, and then excuse themselves by saying that »minor variations in the composition» do not invalidate the major problems, but may only prove that a differentiation has taken place gradually. This, however, is not true, because if granite-looking rocks are considered in the widest sense, there are quartz diorites and granodiorites, which usually form a direct derivation from peridotite and gabbro through diorite, if differentiation sequences on the basis of chemical composition are constructed. After granodiorite, on the contrary, in most of the cases examined in this way, there is a definite gap between them and the actual granites as defined above.

Because, however, the acid plutonic rocks have nevertheless the tendency to occur genetically closely related to each other, some authors, especially those of USSR, and Smulikowski (1958) of Poland, prefer the term »granitoid» as a collective designation for such rocks.

But there are remarkable differences in many other respects as well between granites and granodiorites. Batholith structures are rather common, but they are made up of quartz diorite and granodiorite. Actual granites are often occasional and restricted to tectonized places, or occurring as veins which are indisputably younger than the main mass of the batholith. Thus even in a single batholith, the granodiorite which forms its main rock has a definitely different origin from its granitic portions — either pink veins, or portions gradually grading into granite and displaying all the evidence commonly considered as proving granitization.

But even the rocks fulfilling the compositional requirements set down above for a granite, may still vary very much and in several respects, especially in the relative amounts of main constituents, of accessories, in the grain size, and often also in the relations between micas and hornblende. Sato (1961) remarked, however, that the chemical composition alone does not determine the mechanism of the formation of a granite, but there are many other factors: field evidence, textural features, twinning in plagioclase (Gorai, 1951) *etc.*, have to be considered as well.

In the great number of papers describing some particular granite there is a tendency to build up granite theories on the basis of this description, forgetting that the case described may be a very local one, and that what there appears as an exception may elsewhere be a rule. Examples: Johannsen (1941, p. 137) wrote: »— — — Not only may orthoclase and plagioclase be present, but orthoclase and microcline may occur together»; or: »microcline is much less widely distributed in granite than orthoclase — — —» and »The characteristic feldspar of granite is orthoclase.» Furthermore (p. 145): »In normal granites, however, it (microcline) is much less common than orthoclase.» And yet, in the Precambrian granites the situation is entirely the opposite, microline being by far the most predominant form of potash feldspar present. Schermerhorn (1960, 1961) took one type of Skye granite for unusual, yet this is common among the Alpine granites. Also the pure microcline-albite granites, which are very wide-spread among the latekinematic Precambrian granites, are in his opinion very sparse.

The geologists of Precambrian areas, especially of Scandinavia and Finland, have mainly worked on the true microcline granites. In these orthoclase is mostly uncommon (see p. 24), with the important exception of rapakivi, which contains both microcline of different triclinicities and orthoclase side by side and often in the same grain. This has been tested by x-rays and so contradicts the assumption made by Tuttle and Bowen (1958, p. 98), that »— — — if some of the grains show a microcline grill probably all the potassium feldspar is microcline». Therefore they have mainly based their theories on observations made on microcline granites. Another large group of geologists pays attention chiefly to younger granites with very perthitic feldspar, mostly orthoclase, from which group almost all the examples discussed, in the paper by Tuttle and Bowen (1958) have been taken. The present author has stressed the importance of distinguishing microcline and orthoclase granite groups and discussing them separately (Marmo, 1958a), and he is still convinced that this is the way to approach the problems of granite origin and emplacement.

There is also another reason for the controversies over the granites, and that is the different approach to the problem. Some geologists do it in a fundamentally stratigraphic way. They find out formations and discuss the position of »granites» in the system, as for instance the »Birrimian» granites of West-Africa (*e.g.* Arnould, 1961), which actually contain quartz diorites and granodiorites, and would preferably be termed as »granitoids». The discussion of the origin of granites certainly cannot be based on these rocks. Another kind of approach is that of geologists, who concentrate on finding out whether the granite is magmatic, palingenic or metasomatic basing their assumptions mainly on petrological characteristics. They cannot keep to a cumulative granitoid-term, but must definitely distinguish granite from granodiorite or quartz diorite. Finally, there are geologists, who approach the problem in what is probably the strictest way: For them rock-forming minerals and mineralogy as an indicator of the conditions of formation are of importance. The comparison of these data with experimental findings is essential.

If all these three lines of approach are to proceed separately and without close contact, the result will be increasing controversy. In the opinion of the present author, all the above-mentioned approaches should be combined. No explanation regarding the results of petrological or mineralogical investigations should be controversial — even if it is apparently controversial with the adopted theories.

The modern student of granites cannot be solely a geologist, but must also be a good petrologist, who follows every trend within his science. He must also know sufficient mineralogy to be able to adopt the latest results of this field of science. Also involved is the exploration of physical and chemical processes, as was stressed, for instance, by Walton (1960).

The present paper is actually a new, revised and expanded edition of the paper by the present author, issued in 1962: "On granites". Bull. Comm. Géol. Finlande N:o 201. The rewriting of this paper was caused by the abundance of literature dealing with granites and issued after 1962, which gave many important new facts and deepened our understanding of many questions conneceted with various granites. Therefore, some new chapters have been added in the new edition, and increased attention has been paid to accessory constituents.

TECTONIC GROUPS OF GRANITES

The differentiation of granites or, rather, granite-looking rocks, into different groups is actually as old as the study of granites, because no student of these widespread rocks could avoid finding very different types among them. Furthermore, the compositional differences between granite types have likewise been recognized, though not, however, sufficiently considered in the discussions on granites and their origin.

Sederholm had four groups of granites. Eskola (1932) proposed to divide the Finnish granites into three different magmatectonic types. His starting point was magmatic, but (*op. cit.*, p. 474): »It is of course difficult and in many cases it will probably always be impossible to tell exactly to what extent truly juvenile ichors, derived by squeezing out or by some other way of differentiation from the sima, have been added to the palingenic magma in any particular case». He made, however, an attempt to guess the distribution of the above-mentioned magmatic materials. His first criterion was the presence of other members of the same differentiation series. If these were present down to peridotites, the complex should »in all probability contain much juvenile material». If, on the other hand, a granite is accompanied by only small amounts of more basic differentiates, this »could be presumed to be largely palingenic». Furthermore (*op. cit.*, p. 475): »- - - igneous masses which have given rise to large ore bodies or skarn masses at their contacts should be suspected to be mainly juvenile, while sterile igneous masses would seem rather to be of a palingenic origin». From this point of view Eskola got his magmatectonic types of granites.

Synkinematic granites

Synkinematic granites form an early stage of an orogenic cycle. To this group belong the older Archaean granites of Fennoscandia, which include many primary gneisses, and hardly any non-orientated rocks at all. Eskola (1932, p. 474) remarks, however, that »typical granites (normal-granitic magmas of Niggli) are rather subordinate to granodiorites and quartz diorites covering the widest areas among them». These granites form concordant (with country rock) intrusions, and are easily comparable with the granites of Sederholm's group I. Eskola considers these synkinematic rocks as having derived from juvenile magmas.

Because, however, the granite composition is uncommon among these rocks, the statement that synkinematic rocks are juvenile magmatic does not imply that the actual granites among them are also magmatic. This was, later on, expressed by Eskola (1955) himself when he stated that the potash feldspar of synkinematic granites may to a large extent be entirely of metasomatic origin, or (*op. cit.*, 129): »Today I must - - - admit, that there may be no synkinematic ideal granites of original bulk composition in Finland».

This point will be discussed later in this paper (p. 12).

Latekinematic granites

Latekinematic granites are rocks whose magmatectonic behaviour indicates that they belong to comparatively late stages of the orogeneses. As Wegmann (1930) has pointed out, they often show a diapire-like mode of intrusion in the axial culminations of the old mountain chain. This group includes Sederholm's group II and the latekinematic granites are (Eskola, 1932, p. 477) »in their composition close to the final stage of crystallization differentiation very uniform potash-rich granites, though frequently containing almandite or cordierite, which are perhaps remains of original sedimentogeneous rocks that have never been entirely dissolved». These granites, according to Eskola, »would seem to be largely palingenetic».

Later on, Eskola (1955) defined and revised his opinions about the latekinematic granites, remarking, that typical eutectoid ideal granite composition is common among the latekinematic granites, and that among them (*op. cit.*, p. 129): »metasomatic types with preserved »ghostly relics», or »old design» of stratification are fairly common». And: »There are probably always portions, mixed with rocks of the metasomatic mode of origin by replacement, that have had a liquid phase from which the crystallization has taken place in a truly magmatic way». Later on, Eskola (1960) seems to have abandoned the name latekinematic using instead the term »serokinematic».

Postkinematic granites

Postkinematic granites are, in the opinion of Eskola (1932), best represented in Finland by the rapakivi granite, which, in the absence of traces of movements is unique in the Precambrian. It has intruded as a completely molten magma and remained motionless during its crystallization. Eskola takes as belonging to the same group some Alpidic postkinematic granites, *e.g.*, the granite of Baveno. In chemical composition they are true granites, and not distinguishable on this basis from the latekinematic granites, as was, later on, shown also by Simonen (1948a). They are anorogenic granites.

Finally (Eskola, 1932, p. 477): »It seems inevitable that much material from the wall rocks should have been incorporated with the rapakivi magma, while it seems no less certain that it had a juvenile stock magma». Later on, Eskola wrote (1955, p. 130): »The rapakivi plutons are the purest magmatic granites in our country». At that time, not much attention was paid to the fact that the presence of orthoclase in the postkinematic granites is much more typical of this group than of any other Precambrian granites.

On some other classiffcations

The grouping of Sederholm dealt, in actual fact, with the similar characteristics of granites observable in the field, as were also those used by Eskola in his magmatectonic classification, and it was only to be expected that similar observations would be the basis of any granite classification in so far as it is built up on field criteria. During the following years, the classification of granites was again an object of enquiry, and by several authors. Saksela (1936) took as his starting point the geological mapping in northern Finland. As he wrote in his paper, he encountered difficulties in classifying the granites of the map area on the arbitrary petrological or relative age basis. Therefore he developed his tectonic groups: 1) synorogenic, and 2) lateorogenic. The characteristics of both groups are in many respects the same as those of Eskola's syn- and latekinematic granites. The main criteria are, however, for the former the concordant position with the intruded supracrustal rocks, for the latter the discordant contacts and rounded or irregularly-shaped forms of the granite masses. Thus, in Saksela's opinion (*op. cit.*, p. 282): »- - - die synorogene Tiefengesteinsgruppe in hohem Grade von der Tektonik der superkrustalen Formation abhängig ist». For the lateorogenic granites, on the contrary: »Diese Gruppe ist offenbar ziemlich wenig vom früheren Tektonik abhängig». There is, however, a definite difference between his and Eskola's groups, because Saksela includes in the latekinematic group, rocks from granite to peridotite in composition, the acid members forming, however, the large majority, and (*op. cit.*, p. 284): »Die Gesteine gehen oft allmählich in einander über bilden hiernach zu schliessen eine schöne Differentiationsserie». This statement is entirely inconsistent with Eskola's definition of his latekinematic granites, as well as with all the later definitions of resp. granite, considered in the present paper. It should, however, be mentioned that especially in Central Finland, between Kuru (Matisto, 1961) and Keuruu, there are several basic bodies accompanied by a narrow aplite rim or minor aplite body. The contacts, however, are sharp without any kind of gradation. This kind of occurrence of latekinematic granite can have been controlled there by tectonic circumstances rather than by any differentiation from basic intrusives. Saksela assumed, that his synorogenic granites have been intruded due to tangential movements resembling those of Alpine overthrusts. The lateorogenic granites, on the contrary, are contemporaneous with the »Grundfaltung» as defined by Wegmann, which starts with the folding of overthrusted masses.

This classification of granites into two groups is very similar to that described by Högbom (1928) using the term syntectonic for the older, concordantly occurring granites, and latetectonic for the younger, which are always intruded independently of the pre-existing tectonics.

Shortly before Saksela proposed his classification, also Wahl (1936a, 1936b) made a somewhat similar proposal. He supposed that in an area once covered by an old mountain chain, of which the principal part has been removed by erosion, two kinds of granites are to be found. The older ones have now the appearance of gneissose granites, but they (Wahl 1936b, p. 491): »beyond doubt, originally have been intruded into the surrounding partly sedimentary, partly volcanic material during comparatively early stages of the orogenesis as igneous intrusions, but have received their present character of gneiss granites during following periods of orogenesis». These granites he named prim-orogenic. The younger granites, which, in Wahl's opinion, have a more pegmatitic character, and »are intimately connected with and form part of the migmatites», he named serorogenic.

Furthermore, Wahl defined the postorogenic granites as corresponding to the third group of Sederholm. He adds, however, that they (*op. cit.*, p. 493): »may be postorogenic with regard to the one folding, and preorogenic with regard to the other, and may of course more appropriately be styled intraorogenic». Wahl also strongly stressed that his »prim-orogenic granites» are mostly granodiorites, but that his »serorogenic granites» are mostly microcline granites.

All the classifications mentioned above are, as mentioned in many connections, based on field observations which clearly demand a grouping of the granites into at least two, but usually three classes; and because the theories referred to above were made at a time when the magmatic way of thinking was prevalent among geologists, the magmatic explanation for those groups was clear. But still, already Eskola took palingenesis into account and later on also metasomatic views. In the 1940's, the metasomatic views became more and more important. Read (1948), for instance, spoke about »granites and granites» supporting metasomatic views in a very pungent way, but also strong support for the magmatic views has continued in most countries up to the present day.

Walton (1955), for instance, stressed, that in regionally metamorphosed terrains there is strong evidence for granitization, but magmatic emplacement is not excluded. In unmetamorphosed terrains most, if not all, granite must be magmatic. In the latter case, according to him, the level of thermal energy represented by the granite is completely out of harmony with the regional energy level represented by the unaltered sediments. Therefore he called such granites »disharmonious» referring thereby to a discontinuity in temperature between the granite and its surroundings. In the opinion of the present writer, many postkinematic, especially Alpine granites, as well as Nigerian young granites fulfill the requirements of Walton's disharmonious granites, but this is not necessarily the case with the latekinematic ones.

Yet, whatever the existing theories concerning the origin of different granites, there are two or three definitely distinguishable groups of granites, which are most likely explainable on a tectonic basis.

In the following, the present author will express his personal opinion on the classification of granites, and this will be done also considering both the compositional and mineralogical differences occurring in granites. In this discussion the classification of Eskola — into syn-, late- and postkinematic granites — will be principally used.

SYNKINEMATIC GRANITES

General

As is revealed by the above-cited references, all the authors agree that there is a group of »gneissose granites», very typical of most large Precambrian areas, which represent the oldest »granites», as far as this can be deduced from observations in the field. Furthermore, the chemical composition of these »granites» is not that of granite but usually of granodiorite and quartz diorite, with the actual granite composition occurring as patches or stripes, but seldom occupying any areas of considerable size.

In addition, there are large areas containing microcline porphyroblasts in a quartz diorite or granodiorite matrix, which have a bulk composition approaching that of granite. These also seem to be synkinematic.

If the problem of granites and their origin is to be dealt with, only those portions of the synkinematic »granitoids» which have a true granite composition are of special interest here.

It is beyond the scope of this paper to describe here any synkinematic areas in detail. Some general features, however, are necessary to give a basis for discussion of the granite portions of the synkinematic rocks.

Synkematic »granites» occur often forming huge batholiths, which, at their contacts, often grade without sharp contacts into country rocks, or if these differ much in composition, for instance if they are amphibolites, the contacts may be sharp grading within a short distance, but usually they are concordant with the strike of the country rock. Such batholiths have certain features in common, and especially the banding of alternating acid (pegmatitic or granitic) with more basic (pelitic to amphibolitic) portions, or in such a way that thin sections from a limited, and apparently homogeneous area display textures and mineral compositions from granite to diorite. Bott (1957) described a batholith from Dartmoor, England. In his paper, Bott remarks that the batholith is not homogeneous mass at all, but that the rocks referred to there comprehensively as granite are in fact, to a large extent, tonalites, adamellites, and granodiorites, and (*op. cit.*, p. 46): »within a single mass there is often considerable variation of acid rock types». The same is a very common observation among large synkinematic areas in Finland described by almost every geologist who has ever worked on the Finnish Precambrian rocks. A similar situation is observed on the Canadian shield, within the Precambrian in Russian Asia, and also in West-Africa, including the observations of the present author in Sierra Leone and Ivory Coast. Furthermore, if large coherent areas occur, they are mainly quartz diorites or granodiorites or porphyroblastic granites. The latter rocks deserve here more detailed description and discussion, but before that some other common features of synkinematic areas should be considered.

This is also the correct place to note that in his extensive review of the literature dealing with the granites of North America, Buddington (1959) concludes that the granites emplaced in the epizone are almost wholly discordant; those in the mesozone complex, which are dominant in most basement complexes from Precambrian to Early Cretaceous Ages, are in part discordant and in part concordant, and those of the catazone predominantly concordant.

It is not only the chemical and mineralogical composition which makes the synkinematic areas non-homogeneous. There the material itself may be of very different derivation.

Lyakhovich and Chervinskaya (1965) having investigated several Precambrian synkinematic granites in Karelia, Ukraine and Russian platform, remarked, furthermost, that the high content of sphene, apatite, magnetite, as well as the presence of apatite with pleichroic cores and rounded grains of zircon sometimes enclosed by idiomorphic zircon indicate the important role played by the sedimentary material in the formation of these old, »granites».

In Central Sierra Leone, to the south of the Kangari Hills (Marmo, 1962) there is a large area composed of apparently homogeneous, gneissose synkinematic »gragranites» (Fig 1). A more detailed examination will show very marked non-homogeneity, which, in addition, can be explained as being due to the vicinity of the southern end of a large schist belt. Within this area, there is a zone several hundred meters broad, which contains garnets in abundance, in places also sillimanite. This zone, which is also richer in quartz than the gneisses of the environment, extends for several miles in length, weakening southwards and sideways, then fading into granodiorite. Following this zone northwards, it grades into stronger gneissose rocks with increasing amounts of quartz, and finally into garnet-bearing quartzite which forms a part of the interior of the complex schist belt of the Sula Mountains (Wilson and Marmo, 1958) and Kangari Hills (Marmo, 1962). Furthermore, within the same schist belt, »banded ironstones» occur. They are chiefly made up of a garnet-cummingtonite quartzite rich in magnetite, and often form a part adjoining the fore-mentioned quartzites. Therefore it is very striking to find magnetite-rich strips also in the synkinematic gneisses, always associated with the fore-mentioned garnet-bearing gneiss. At the northern end of the Sula Mountains, similar magnetite-garnet-cummingtonite quartzite continues beyond the schist belt into the synkinematic gneiss forming there a comparatively well preserved strip some hundred meters in width and roughly 1.5 km in length.

In this connection it may be mentioned that according to Pichamuthu (1961), in southern Mysore State, the so-called Peninsular banded gneiss has been transformed into coarse-grained charnockite in such a way that the gneissic foliation can often be traced right through the charnockite patches.

At several places, the synkinematic rocks of Central Sierra Leone contain hornblende-bearing patches and strips, which sometimes may contain some pyroxene as well. Mostly they are just patches of varying size and shape; but in some cases they can also be explained, as occasional occurrences of large inclusions of amphibolite in the gneiss often mantled by a zone — from a few decimeters to tens of meters in width — containing hornblende.

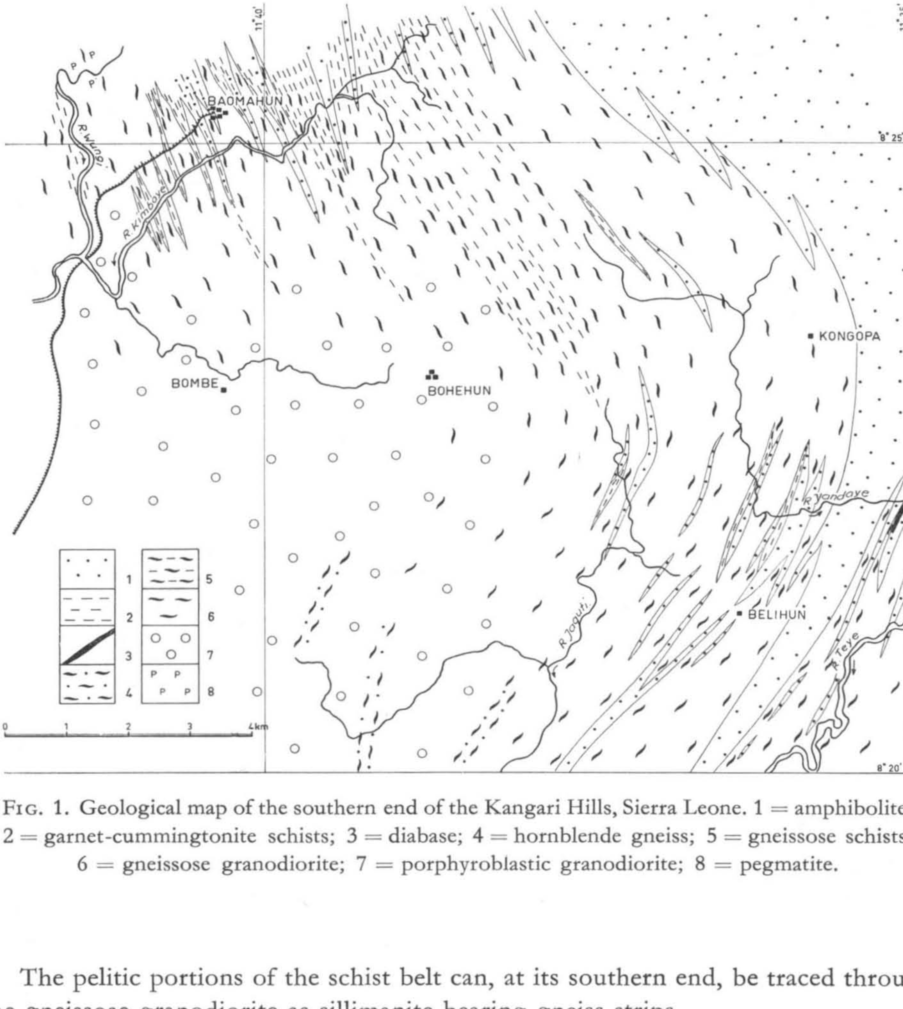


FIG. 1. Geological map of the southern end of the Kangari Hills, Sierra Leone. 1 = amphibolite; 2 = garnet-cummingtonite schists; 3 = diabase; 4 = hornblende gneiss; 5 = gneissose schists; 6 = gneissose granodiorite; 7 = porphyroblastic granodiorite; 8 = pegmatite.

The pelitic portions of the schist belt can, at its southern end, be traced through the gneissose granodiorite as sillimanite bearing gneiss strips.

On the other hand, still keeping to examples from Sierra Leone, there are large and homogeneous diorite bodies enclosed by the synkinematic granodiorite. The contacts between both rock types are gradational and form a wide zone. Thus, the diorite is embraced by an »aureole» of more acid rocks which are often gneissose and grade into massive granodiorite, sometimes porphyroblastic.

Furthermore, the eastern part of the southern end of the Kangari Hills schist belt is composed of fine-grained amphibolites, probably primarily basaltic flows (Marmo, 1962). Also there the embracing granodiorite is hornblende-bearing and contains clusters and strips of similar fine-grained amphibolite.

The titanum-contents of magnetites extracted from different rock types of the schist belt and embracing rocks have been determined (Marmo, 1959). Thereby it was found that among the synkinematic rocks there are those with less than 0.3 % TiO_2 and those with 0.7—1.17 % TiO_2 in magnetite; the latter occur in close association with intrusive diorite, or are themselves hornblende-bearing. The rocks shorter in TiO_2, on the contrary, could often be proved as deriving from sediments of pelitic or related composition.

Consequently, the gneissose synkinematic rocks of Central Sierra Leone contain portions which primarily have been sedimentogeneous, volcanic or intrusive, and there are definite indications proving that the continuation of the schist belt is inside the synkinematic rock area, mostly entirely masked by later geological events, but partly still discernible.

Another example will be taken from Central Finland. There is a large area indicated on the geological map as granite, but which is mainly covered by granodioritic often gneissose rocks, but still more often by porphyroblastic granodiorite. They contain abundant amphibolitic, porphyritic, mica schist and pelitic inclusions. The whole area is typically synkinematic. If minor portions of this area are examined, still there appear large variations both in the texture and composition. West of Vilppula, such inclusions are large and abundant, and around them large areas are characterized by strong gneissosity. At the northern end of Lake Tarjanne there is a strongly altered area of acid volcanics, partly converted entirely into quartz diorite. At Keuruu there is an apparently homogeneous area of porphyritic acid rocks grading in the south into typical gneisses. Still further to the north, there occur large and continuous zones within this area containing cordierite and garnet as well as easily discernible relics of sedimentary structure.

At Virrat, some 60 km W of Keuruu, Finland, gneissose granodiorite is hornblende-bearing and contains abundant inclusions of intermediate volcanics. In the south, the hornblende is absent, inclusions are of mica schists and often the gneiss contains garnet. Furthermore, the composition of gneiss is granitic, as well as to the SW of Virrat, where acid volcanics, leptites and mica-schists grade over into granite-gneiss and often further into gneissic granite. There the heterogeneity of acid rocks is also displayed by irregular distribution of aeromagnetic anomalies indicating a very random distribution of magnetite in otherwise similar granodiorites and granites.

In actual fact, the difference between the original materials of the recrystallized rocks is displayed by the distribution of some minor constituents in synkinematic and latekinematic granodiorites and granites. So, for instance, for the granitic rocks of Osnizk, Russia, Matkovskiy (1956) reports:

	Zircon	Magnetite	Ilmenite	Sphene	Leucoxene	Apatite
granodiorite	0.07	0.46	0.03	0.32	0.01	0.12
granite	0.10	0.45	0.10	0.06	0.03	0.05
aplite	0.03	0.30	0.20		0.02	0.01

All these examples prove that the areas considered as synkinematic are non-homogeneous, but still predominantly composed of rocks of a quartz diorite or granodiorite composition. Furthermore they indicate that whatever the present material is, there are clear indications that primarily very different materials must have been present, and that actually magmatic material is hardly more abundant than are the sedimentary and volcanic materials. According to Matkovskiy (1956), for instance, the zircon of such rocks is mostly of relictic character, as has often been observed by students of similar rocks around the globe.

Homogeneous portions of the synkinematic areas

But it is also evident, that among the gneissose synkinematic rocks, comparatively homogeneous bodies may also be present. Such bodies usually go over gradually into gneissose rocks often showing sedimentary relic texture. Some of these bodies are even-grained and quartz dioritic in composition, but they seldom form any really large coherent bodies. Often they occur in batholiths. Such bodies have obviously had a molten stage in their evolution, and — this is a generally accepted opinion — they may be results of a palingenic remelting of sediments. In some cases, as at Keuruu in Finland, insets of plagioclase occur, also proving such an assumption. At Keuruu, however, the situation is even more complicated, because (map of Fig. 2) within a comparatively small area — 10 km by 10 km in size — gabbro, diorite, quartz diorite and granodiorite, all probably to be considered as synkinematic, occur. In other words, a sequence of differentation may be established there, and — this is of importance — the contacts between the members of the series mentioned are comparatively sharp, the gradations being occasional. As will be pointed out later on in this paper (p. 24), the potash feldspar forming porphyroblasts is of inferior triclinicity in this particular area, thus possibly indicating a somewhat elevated temperature of formation. Such potash feldspar is in general exceptional within the synkinematic rocks. All these features may prove the presence of magmatic synkinematic rocks, as well, which actually agrees very well with our knowledge of the early orogenic evolution. Whether the magma yielding these rocks is juvenile or palingenic is another question, discussion of which is outside the scope of this paper. Yet it may be mentioned, as a personal opinion of the present author, that keeping in mind the thickness of the earth's crust as well as the information about it so far available, the palingenic origin would be more attractive than the juvenile one, just as this possibility has already attracted Sederholm and Eskola.

In his paper, Simonen (1960) seems to pay much attention to gneissosity and homogeneity as criteria for the division into syn- and latekinematic plutonic rocks (*op. cit.*, p. 9): »Sharp separation of the plutonic rocks in the Tampere area into synkinematic and late-kinematic types is not so easy as in southern Finland, owing to the fact that there are many transitional varieties, ranging from gneissose synkinematic types to massive late-kinematic plutonic rocks». I do not think that this state-

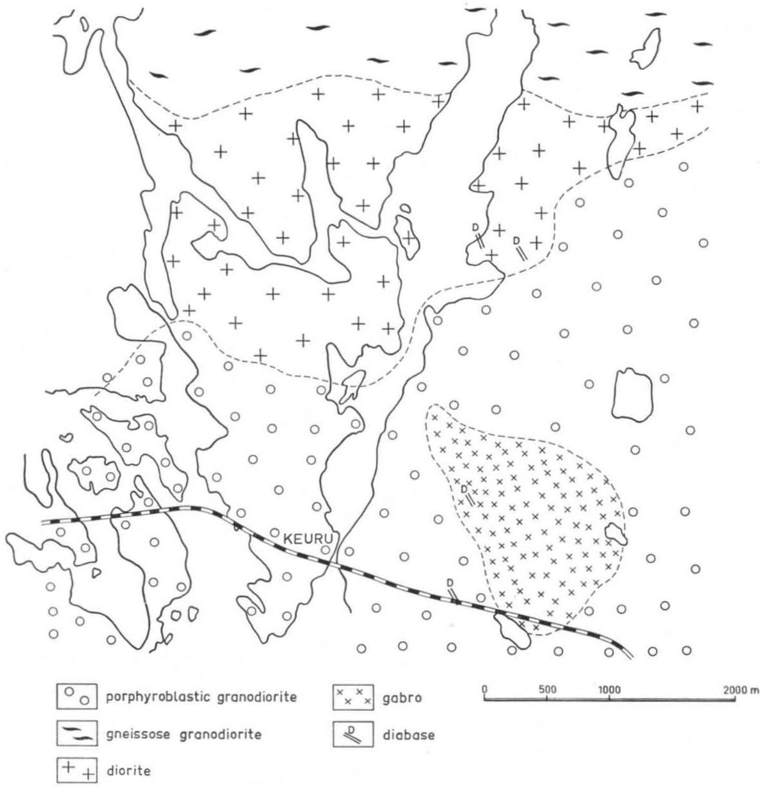


FIG. 2. Geological map of the area around Keuruu, Finland.

ment of Simonen should be taken literally, because the criterion must be, in this case, a tectonic one, unless the gradation is not considered as a latekinematic granitization, which, however, does not appear to be the case in his paper. On a similar basis one must reject his statement that Saksela's classification into syn- and late-orogenic groups does not refer to the different ages of these groups, but that (*op. cit.*, p. 11): »It shows only the different manner of occurence of the plutonic rocks in the principal Svecofennidic schist zone and outside it. It seems probable that the intrusions into different tectonic environments have taken place simultaneously from a common parent magma». For these statements it is very difficult to find any proof, particularly, because in Saksela's areas the majority of the synkinematic rocks have originated from sediments.

Porphyroblastic rocks

This is a group of rocks which is essential to synkinematic areas everywhere, often forming comparatively homogeneous bodies. In West-Africa and southern

FIG. 3. Tor-like hill composed of porphyroblastic granodiorite. Sierra Leone.

India they frequently occur as tor-like bodies (Fig. 3) strikingly elevated from the topography (Marmo, 1956 b). In Finland they often occur in the form of hillocks and ridges making the landscape rocky and broken, and they occupy large areas in the central part of the country.

The names porphyroblastic granite and granodiorite are here used for the rocks of mainly granitic bulk composition containing large, usually pink insets of feldspars (Fig. 4) and white insets of oligoclase or quartz in a matrix usually of quartz diorite or less frequently of granodiorite composition. Such rocks have often been referred to as »porphyritic». The present stage of our knowledge, however, strongly supports the view that these insets are usually porphyorblasts and not phenocrysts.

FIG. 4. Porphyroblastic granodiorite, Hyrkkälä, SE-Finland. Photo A. Vorma.

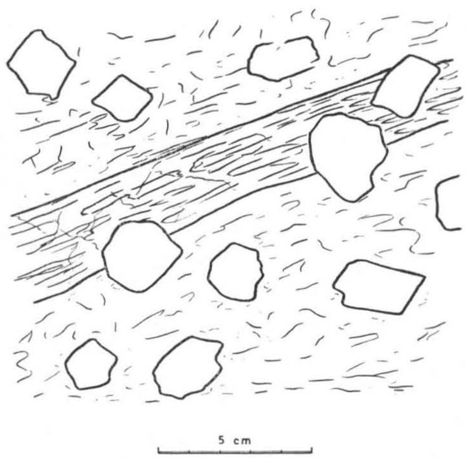


FIG. 5. Porphyroblasts of microcline growing across a fracture. Gbengbe Hills, Sierra Leone.

The geology of areas occupied by porphyroblastic granites is very similar in the different regions examined by the present author, and elsewhere as described by other authors. One of the best examples is the Gbengle Hills, Central Sierra Leone (Marmo, 1956b). There the hills themselves, 4 km by 6 km in size, are composed of homogeneous porphyroblastic granite, and the whole complex is surrounded by an »aureole» of gneiss, often of migmatitic character. The insets of the porphyroblastic granite may be as much as 1 to 2 inch across, and they are composed of microcline, oligoclase and quartz embedded in a groundmass consisting of guartz, oligoclase, biotite and small amounts of microcline, the last-mentioned mineral occurring only in the interstices of other minerals (or in fissures). Thus the main potassium-content of the matrix of this rock type is fixed into biotite.

In Finland such examples are abundant. An area of porphyroblastic granite in Central Finland, between Vilppula and Haapamäki, which is of the same size as the Gbengle Hills, but much less hilly, and is likewise surrounded by gneisses may be mentioned here. In Central Finland, around Äänekoski, the situation is exactly similar, but the dimensions are larger.

Smithson (1963) has described, for instance, similar porphyroblastic granite from the Flå area in Norway. There the composition of the granite falls into the range of quartz monzonites. The K-feldspar porphyroblasts consist of maximum microcline and contain as inclusions oriented plagioclase grains, similar to those occurring in the matrix. This porphyroblastic granite is likewise surrounded by banded granodiorite gneisses, the migmatites and augen gneisses being common just outside the granite contacts.

The origin of such porphyroblastic granites has been thoroughly discussed by the present author (Marmo, 1956b), who suggested, on the basis of detailed observations within the Sierra Leonean occurrences, that they have also derived from sediments. The potassium, which is abundant in clays, has partly, due to palingenesis or softening by the heat of the material, been concretionary concentrated into porhyroblasts. This would explain why the matrix of these rocks is homogeneously quartz dioritic or granodioritic, and why the porphyroblasts frequently grow across the fractures (Fig. 5) and also occur in undisturbed form in the surrounding gneisses and in the amphibolitic strips adjoining or enclosed by the porphyroblastic granite. The emplacement of these granites, as judged by observations in the field, seems in many cases to have taken place due to a doming-like mechanism, as well as the joint action of pressure and a local increase in the temperature, where the doming began. This may also explain why in the investigations carried out by Matisto (1962), orthoclase has sometimes been found in similarly shaped rocks of the Tampere area and according to Marmo, Hytönen and Vorma (1963) in some area around Keuruu, Central Finland and in eastern Finland. Kosoy and Kotov (1965) described some porphyroblastic granites from Central Asia, and they found out, that there the potash feldspar of the porphyroblasts shows less triclinicity than that of the groundmass, and ascribe this phenomenon to the difference in the relative rate of growth of the porphyroblasts and of the groundmass.

Mostly, however, the porphyroblasts consist of primarily grown microcline. As has been deduced from his observations, Cannon (1965) states the same for the porphyroblastic granites of Bartica, British Guiana, as also Röhlichova (1964) for certain porphyroblastic granites of Central Bohemian pluton.

Porphyroblastic varieties also often occur in the marginal parts of quartz diorite or granodiorite bodies, the latter being conspicuously rich in oligoclase. Orville (1961) explains this feature on the basis of experiments he carried out for the K/Na replacement. He found that the Na/K ratio in an alkalichloride vapour phase in equilibrium with two alkali feldspars increases with falling temperature; and thus a vapour phase moving from one rock into a second, cooler rock, would cause replacement of Na-rich feldspar by K-rich feldspars in the cooler rock and vice versa. This mechanism of alkali metasomatism has been demonstrated on a small scale in the laboratory.

Sudovikov *et al.* (1965) ascribed the formation of porphyroblastic granites of the Aldan shield, Siberia, to processes similar to the granitization. They described continuous sequence from biotite gneiss grading through porphyroblastic gneiss and granite gneiss into homogeneous porphyroblastic granite.

Synkinematic granites

Among the synkinematic rocks, as mentioned above (p. 12) the portions of true granite composition are subordinate, or they may even occur only occasionally. From what was been written above, however, it may be seen that there are instances where the granite may also be more abundant than usual, and in such cases differentiation

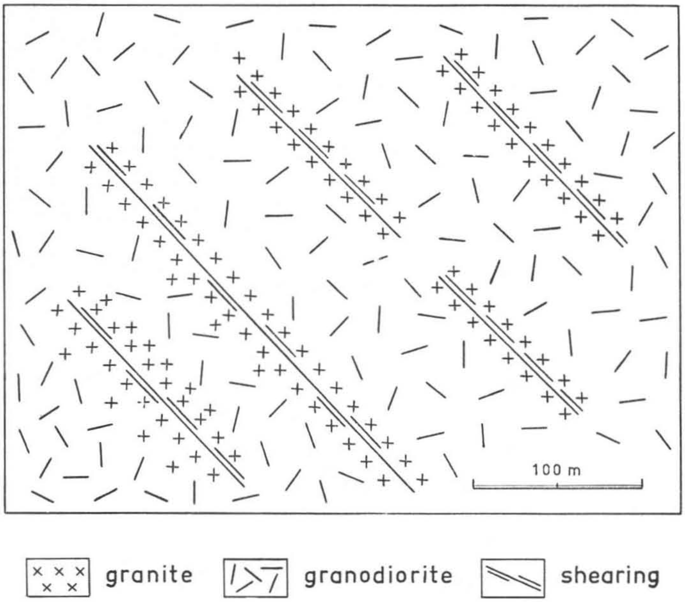


FIG. 6. The granitic portions follow the sheared lines in a granodiorite mass. N of the Sula Mountains, Sierra Leone.

series, within a single batholith, from gabbro up to granite may be established. But even then the term granite must be considered conventionally, because if a true granite of an ideal composition occurs there it is definitely younger than other members, and a discontinuity — gap — appears between granodiorite and granite. Up to granodiorite, on the contrary, such sequences may often be observed. The case of Keuruu, Finland, was mentioned on p. 15. Raguin (1957) in the second edition of his textbook, refers to Daly (1914) and discusses »les massifs composites», presenting several examples of such cases. Furthermore, he also pays attention to the co-occurrence of plutonic and volcanic rocks, both being members of the same family as defined by chemical and mineralogical composition (»les séries lithologiques»). In such cases, the differentiation diagrams likewise display a chemical evolution in the differentiation.

But there are large batholiths which cannot be treated in the same way, and they form a large majority of the synkinematic batholiths. In such cases the portions approaching the composition of granite are restricted to tectonically disturbed portions, as in Sierra Leone, where respective granitic zones are very narrow and follow, in some cases, fractured zones, while in others they appear in strongly bended strata within the batholith. The same has been repeatedly observed by the present writer in the synkinematic granodiorite masses in Finland. Fig. 6 illustrates one such typical example. In such a case it may be easily seen, that from the fractured portion richest in potassium its amount decreases outwards gradually but rapidly and finally the granodiorite composition, characteristic of the bulk of the massif, is attained. When one examines this phenomenon under the microscope, it is easy to discover that the microcline is younger everywhere than any other constituent of the rock, and that it occurs mainly as infilling of fissures or in the interstices of other constituens. Such cases may, of course, be interpreted in two ways: either granite appearing in fractured zones has caused granitization in the environment, or the granite is produced by an accumulation of potassium transported towards the fractured areas, which correspond to the places of lowest free energy.

Saha and Bandyopadhyay (1964) have investigated an area made up of biotite granodiorite, 11 sq. miles in area, around Kuyali, Singhbhum district, Bihar (India). They found out, that on the basis of modal analyses and by superposing a square grid pattern over the whole area, the procedure of analysis of variance revealed considerable local variations in composition. Furthermore, they could demonstrate, that the K-feldspar-rich residuals had migrated towards the low-pressure border region of the granodiorite body.

Among the earliest papers describing such phenomena is that by Simonen (1948 b) who considered the synkinematic intrusions (in southern Finland) as magmatic, but (*op. cit.*, p. 21): »- - - the content of the alkalies, especially K_2O, has slightly increased secondarily, during the advance of the migmatite front». Furthermore, he observed that such an alkali increase is especially typical of the gneissose varieties. The appearing gneissosity is, in his opinion, caused by a purely mechanical process, and it was, afterwards, attacked by new microcline-rich material, and (*op. cit.*, p. 32): »- - - fine-grained granitic fabric has been formed secondarily between the crushed crystals of the primary rock». At the time, Simonen obviously thought that granitic material had invaded from the outside and caused the granitization of granodiorite. The present author would explain similar phenomena in such a way that the »granitizing» potassium derives from the granodioritic material itself (see p. 28).

Similar observations probably also led Eskola (1955) to deduce, that among the synkinematic rocks there are probably no true granites of primary bulk composition.

Fig. 7 illustrates very well how microcline occurs usually in synkinematic rocks, clearly indicating that this mineral is younger than the other constituents of the respective rock.

Thus it may be safely concluded that if, among the synkinematic rocks, granites occur, they have very probably attained their present composition in some way other than magmatic. They are results of a potassium metasomatism.

According to the review of Buddington (1959), for the batholiths of North America, the granitization has played a role of only subordinate significance in the mesozone, and yet, according to Buddington, the Precambrian basement belongs predominantly to this zone. The reliance has been mainly on magma emplacement. This, however, has been doubted by Buddington himself (*op. cit.*, p. 740): »Hypothe-

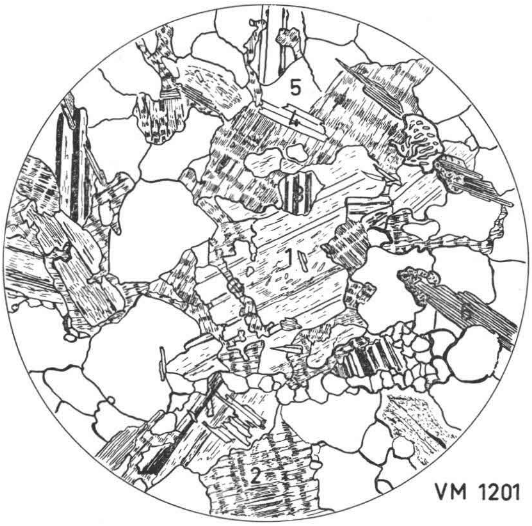


FIG. 7. Microcline occurring in a synkinematic granite as the youngest constituent of the rock. Sierra Leone. 1 = plagioclase; 2 = microcline; 3 = younger, albitic plagioclase; 4 = muscovite; 5 = quartz; 6 = biotite. Magn. 40 x.

ses, in general, as to the respective roles of magma and of metasomatism in the emplacement of granitic plutons are conflicting, and the problem remains one demanding critical studies and more dependable criteria».

Cannon (1965) on the other hand, when discussing the granites of Bartica assemblage, British Guiana, concluded that some synkinematic rocks there have acquired granite composition presumably through granitization, itself a result of potash metasomatism.

Potash feldspar of synkinematic rocks

In earlier geological literature on the Finnish basement, there are some scattered notes on the orthoclase also occurring in the synkinematic rocks, in which the microcline was always taken as the predominant form of potash feldspar. Later on, however, mainly due to the works of Mäkinen (1917) and Eskola (1929), common opinion denied the presence of orthoclase in the synkinematic rocks, and, as a matter of fact, all potash feldspars extracted from such rocks, in Finland, Sweden, Russian Karelia, Sierra Leone *etc.* proved to be microclines of high triclinicity.

Furthermore, the microcline occurs in these rocks mainly as interstitial infillings, or in the form of porphyroblasts — in general, as a younger constituent than the bulk of the rock.

Actually such a situation was somewhat surprising, because it was still to be expected, that the conditions during the formation of synkinematic rocks could not be only those of the granitization of which microcline is truly characteristic. Either elevated temperatures or rapid crystallization (see p. 64) certainly should have appeared there sometimes, at least locally. Therefore it was thought that this may have been due to the insufficient number of the triclinicity determinations carried out.

Matisto (1962) found orthoclase in the granodiorites of the area around Tampere. These rocks are porphyroblastic synkinematic rocks. Simultaneously the present author made investigations in Central Finland at Keuruu, and Vorma around rapakivi areas in SE-Finland. These investigations revealed the fact (Marmo, Hytönen and Vorma, 1963), that there are, within the synkinematic rocks of Finland at least three well limited areas, for which the presence of potash feldspars of inferior triclinicity (including orthoclase) besides microcline is characteristic. Furthermore, in all these cases this kind of potash feldspar forms porphyroblasts, the interstitial potash feldspar still being in most cases, highly triclinic microcline. Outside these areas, indicated in Fig. 8, all potash feldspars so far investigated have been microcline with the triclinicity more than 0.8. For a certain reason I will stress, that here potash feldspars of varying and low triclinicities (less than 0.5) are common. Possibly the lowest values (around 0.0) could be termed orthoclase, but there still remains the possibility that the low triclinicity is ostensible, and caused by balanced, sub-x-ray twinning. At least in some cases evidence for such a possibility exists.

The triclinicity is variable also in a single sample, sometimes even in a porphyroblast (Fig. 9) or in a single grain. Below is an example of the triclinicities of separate grains within the same thin section (Keuruu, 30/KH/62):

grain	1	triclinicity	0.0—0.5	no max.
»	2	»	0.0—0.6,	max. 0.0—0.2
»	3	»	0.0—0.75,	no max.
»	4	»	0.0—0.85,	max. 0.0—0.2
»	5	»	0.0—0.55,	max. 0.25

Such potash feldspars are, however, exceptional within the synkinematic areas, and they indicate exceptional conditions, which are not characteristic of the synkinematic conditions in general. It seems to the present author, that as a whole we are entitled to say, that the presence of highly triclinic microcline as the sole form of potash feldspar is the characteristic feature of synkinematic granites and granodiorites, and that the main exceptions so far observed are connected with the porphyroblasts of porphyroblastic varieties.

Granodioritization or granitization

It has been mentioned above (p. 13) that the continuation of sediments occurring within the schist belt of the Kangari Hills, Sierra Leone, can easily be traced

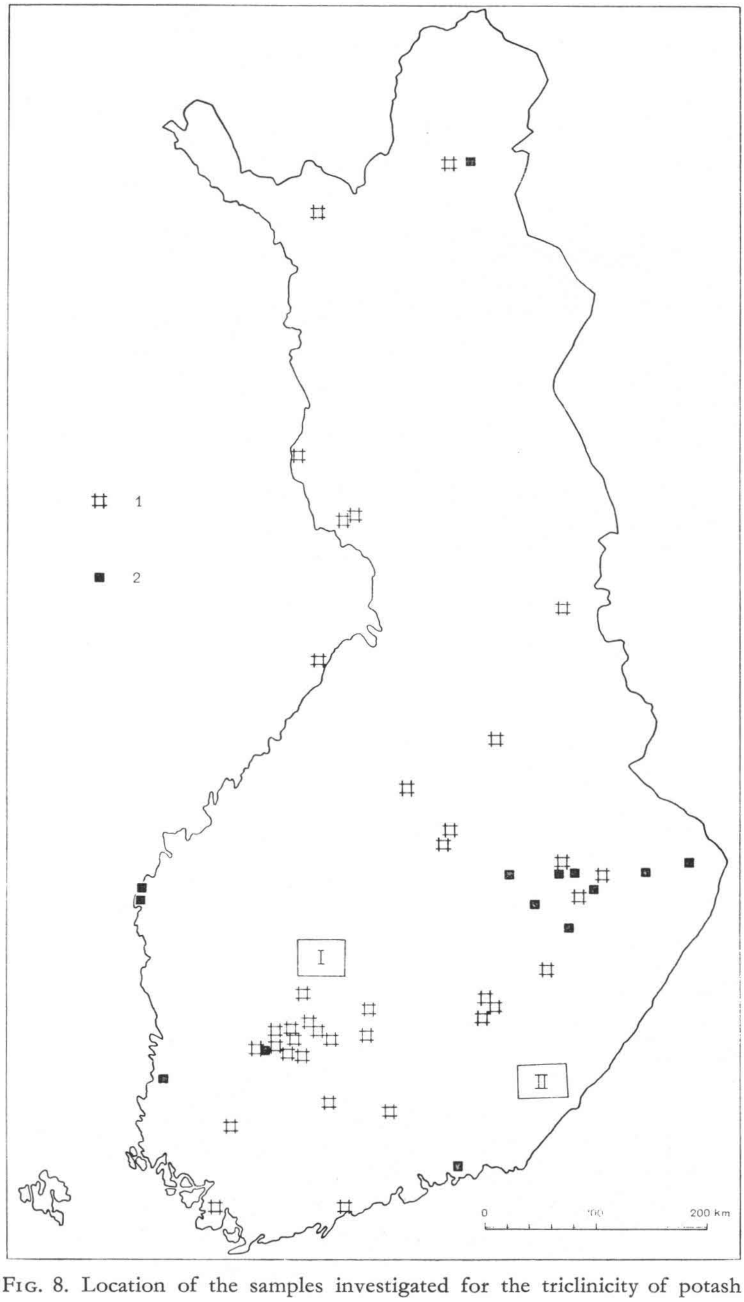


FIG. 8. Location of the samples investigated for the triclinicity of potash feldspar in synkinematic acid rocks in Finland. 1 = microcline; 2 = orthoclase; I = map sheet 2232 and II = map sheet 3134, there areas are especially characterized by the presence of low triclinicity values in the porphyroblasts. (Marmo, Hytönen and Vorma, 1963, p. 57).

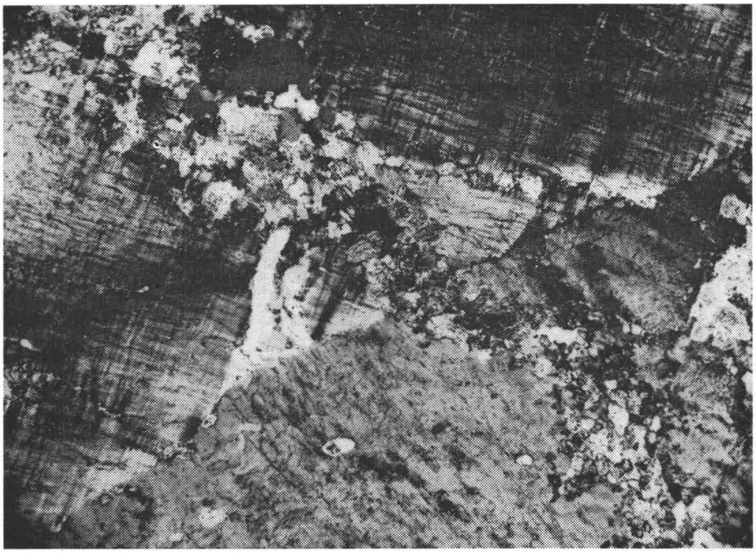


FIG. 9. Orthoclase and microcline occurring in the same porphyroblast. Granodiorite (33/VM/62, Fig. 1, area 1). N +, magn. 40 x. (Marmo, Hytönen and Vorma, 1963, p. 63).

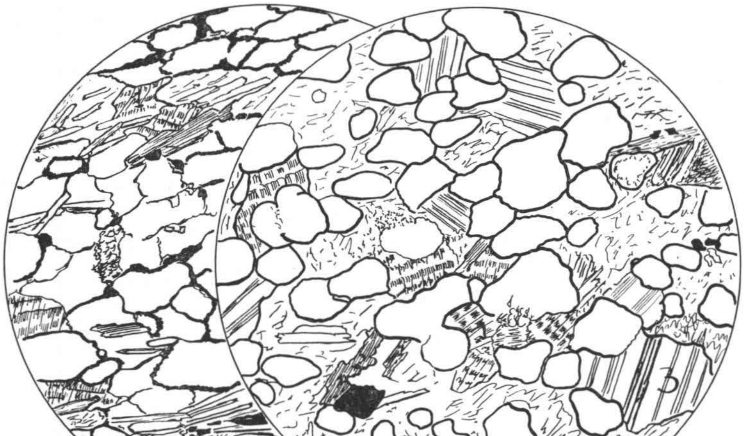


FIG. 10. Interstitial microcline in a slightly granitized magnetite-cummingtonite quartzite (J 1224) and in a gneiss rich in quartz (J 723). Kangari Hills, Sierra Leone. 1 = microcline; 2 = biotite; 3 = plagioclase; white is quartz; solid black is magnetite. Magn. 40 x.

FIG. 11. Garnet-bearing amphibolite from a well-preserved strip within granodiorite. Amphibole mostly biotitized. Sierra Leone. Magn. 40 x.

through the synkinematic granodiorites. There also the quartzites of the interior of the Kangari Hills continue through the granodiorite — granite area, being marked by granodiorites conspicuously rich in quartz. Fig. 10 illustrates two examples of rocks from the quartzites going over into granodiorite. The left-hand thin section bears clear evidence of the granitization of a magnetite-bearing quartzite in which an interstitial microcline occurs; in the right-hand figure, a similar microcline has attacked sericite quartzite, which, in this case, has attained an almost granitic composition, but the rock still contains abundant well-rounded »clastic» grains of quartz.

Within the schist belt of the Kangari Hills, the mica schists are sparse. It seems that they occurred originally around the amphibolites, but were almost completely converted into gneiss and granodiorite, because, along the eastern side of the schist belt, there are within the granodiorite gneiss numerous relics of enclosed mica schists and lenses exceptionally rich in biotite and quartz, which are doubtless signs of the original material of pelitic composition. It may be, that the shortage of argillaceous sediments among the metamorphites of the schist belt is the result of the »granitization» of most of those previously existing in the geosynclinal sedimentation pile. In such cases, to obtain the composition of granodiorite, the addition of sodium is necessary. The granites or granodiorites, evidently originating at the expense of the quartzite, are always pale, and chiefly consist of quartz, oligoclase and microcline, the latter being the youngest constituent.

The tendency of the synkinematic granitic-looking rocks to attain granodiorite composition is worth consideration. There are both even-grained and porphyroblastic granites everywhere in the Precambrian areas which are extensively recrystallized, but contain no or only a little potash feldspar. The garnet-sillimanite or cordierite-oligoclase gneisses south of the Kangari Hills or of Central Finland often contain only very minute grains of microcline or none at all (Fig. 11). The potassic varieties of the synkinematic granites are usually connected to disturbed areas and to definite zones. Such conditions have led the writer to suggest that first phenomenon of synkinematic metasomatic processes leading to granitization elsewhere is »granodioritization» (Marmo, 1958 a). Potassium metasomatism may follow at a later stage completing the »granitization».

The composition of plagioclase in the synkinematic granodiorites does not vary very much, being in general 20 to 30 % An. The granodiorites of an area 30 km by 30 km in size, at Pihlajavesi, have an An-content of plagioclase varying from 23 to 32 %. In hornblende granodiorites it often reaches higher values, rising exceptionally up to An_{35} or even more. Engel and Engel (1953) remarked, that if the gneiss-granites originated due to an extensive post-depositional addition of potassium, its homogeneous distribution throughout large areas would be difficult to explain. To the foregoing it may be added, that it is also difficult to explain on the basis of sodium metasomatism, why the ratio An:Ab of the synkinematic granodiorites and granites is so uniform; on the other hand, the distribution of potassium in the granites is not very uniform, but its abundance is mainly characteristic of definite, usually comparatively narrow zones. The homogeneity of its distribution is more conspicuous in the latekinematic granites.

To explain the proposed »granodioritization» so that the interpretation agrees with the facts, *i.e.*, 1) uniform and pervasively distributed sodium; 2) the comparatively small variations in the composition of the plagioclase; 3) the small volume of the standard cell of the granodiorites (Marmo, 1955), it may be assumed that the granodiorites are products of the direct, isochemical recrystallization of the materials of appropriate composition. Now, however, the synkinematic granodiorites and granites (around the Sula Mountains and Kangari Hills of Sierra Leone, as well as in many places in Central Finland) seem in general to have originated from clay and sand sediments, which all contain considerable amounts of potassium. According to Pettijohn (1949, p. 271) the shales of the Missisippi delta contain 2.30 % K_2O, but only 1.51 % Na_2O. The average for the shales is respectively 3.24 % and 1.30 %; and the average for graywacke is 2.6 % and 1.0 %; the Litorina clay of Vähäkyrö, Finland (determined by the Geol. Survey, Finland) contains 3.96 % K_2O and 2.19 % Na_2O, and so on. The ratio K_2O:Na_2O of granodiorites on the contrary, is in general less than 1, sodium being there in excess of potassium. Therefore, it seems that an explanation other than that of sodium metasomatism is necessary here: it may be assumed to be the removal of potassium during the recrystallization (whereby also some quartz may be removed). Engelhardt (1961) has assumed that especially the clay sediments contain primarily pore solutions rich in sodium, and thus the sodium-richness of granodiorites may be explained. Yet, however, this amount of sodium is hardly sufficient to decrease the ratio of K_2O to Na_2O as much as would be necessary here, and even then the removal of potassium very probably takes place to a considerable extent. Both above-mentioned alternatives have also been considered by Engel and Engel (1953, p. 1078): »- - - the gneiss could be thought of as a venitic migmatite, whose high Na_2O/K_2O ratio is the result of preferential extraction of potash, conceivably to form the potassic, granitic ichor which now forms the migmatizing and granitizing substances in the gneiss. The alternative is that soda, or sodium ion, has been added to the sediment by some post-diagenic process». They consider the former alternative as more likely. Also in the opinion of the author the »granodioritization» is a result of extraction of potassium. The high total alkali content of some synkinematic granites is thus a result of the leaching away of some quartz, as well. Both removed elements are then responsible for the formation of certain simple pegmatites often accompanying synkinematic granodiorites, and also explains the ample quartz »Schlieren» typical of many gneissose synkinematic rocks. The further destiny of the extracted potassium is linked with potassium metasomatism, which will complete the granitization. The greatest part of the potassium which has been removed, however, probably re-appears at a later stage of the orogenic evolution (see p. 36).

Tuominen (1961), who has made very detailed investigations of the synkinematic granodiorites of the Orijärvi region in Finland, came to the conclusion that there, during the folding, the elements migrated from the limbs toward the axial zone, down the gradient of shearing stress and pressure. Thereby, the contracting limbs became basified while granitization took place in the expanding axial zone.

This kind of removal of potassium and silica from a rock has been termed by Ramberg (1944), »chemical squeezing» and owing to it, during recrystallization flow, the most diffusive constituents (K, Na, Si, Al, *etc.*) would tend to concentrate in the low-pressure areas.

In this connection we must also consider the fact that sodium too may be expulsed from pre-existing sediments (or other rocks), and re-appear in a way similar to that of potassium in places corresponding to the lower free energy. Numerous examples of this kind are available in regional-metamorphic rocks known as »ader gneiss» or »veined gneiss», often containing concordant veins mainly composed of plagioclase, microcline and quartz separating narrow strips and bands of mica schist which is often intensely folded (Fig. 12). In some cases, such plagioclase-rich material brecciates the older rocks, and then it can be said, that it occurs as metasome of plagioclase migmatites.

A rather common feature within certain synkinematic granitic rocks is that, together with potash feldspar replacing plagioclase, a younger albite is formed as rims and separate grains. This is product of sodium released by replacing potassium.

FIG. 12. A portion from an intensely minor-folded veined gneiss. Vuolinko, Eastern Finland. 1 = plagioclase-rich pegmatite; 2 = folded mica schist.

According to Rogers (1961), at least in some cases, such albitic rims around more basic plagioclase, as well as separate albite grains have been crystallized simultaneously with the potassium feldspar.

Backlund (1953, p. 98—99) also surmised different conditions of emplacement of different granites saying: »The calc-alkaline or geosynclinal series of »igneous rocks» is emplaced under narrowing conditions of mouldable areas of the Earth's crust *i.e.* with tectonical pressure, while the alcaline or nonorogenic series of »igneous rocks» has been emplaced under expanding conditions of rigid parts of the Earth's crust, *i.e.* with tensional and block tectonics». Under such conditions, again, the expulsion of potassium from the stress areas and subsequent granodioritization are to be well expected in the synkinematic rocks.

As regards granitization, Bowen (1947, p. 275) says: »At levels that ever come under observation I would expect that the action was ordinarily effected through unusual access of heat due to the intrusion of a magma. The granitization of surrounding rocks would, in this view, be a subsidiary attendant process».

Several other authors support different views and even accord the main role in the formation of granitic rocks to granitization. The modern representatives of the French school, Perrin and Roubault (1939) have strongly supported the reaction in a solid state as a cause of granitization. These ideas were later on developed, and the geological significance of solid diffusion discussed theoretically by Ramberg (1944).

The fact that microcline is mostly the only potash feldspar of the synkinematic granites under discussion, together with the experimental findings of Goldsmith and Laves (see p. 62) supports the assumption that the final stage of granitization — the addition of potassium — took place at a temperature certainly below 600° C, probably at 500—550° C. A temperature slightly lower was estimated by Marmo and Hyvärinen (1953) from the conditions of formation of myrmekite, using as a »thermometer» exsolutions in certain co-occurring sulphide minerals. Kullerud and Neumann (1953) state 440 $\pm$ 25° C as the most probable temperature of granitization, basing their assumption on the FeS content of sphalerite. Also, the fact that the most typical metamorphic facies of old Precambrian synkinematic granites is the amphibolite facies favours the possibility that the granitization takes place at a temperature not much over 500° C, very likely somewhat below this point.

We do not know at what depth granitization processes are taking place. The lowermost level of the sial shell is believed to be 25 km. The thickness of the lithosphere is assumed to be 16 km, and that of the geosynclinal sedimentary beds ranges from 2 to 4 km. According to Daly (1933, p. 175), however, some local, geosynclinal prisms of stratified rocks have a maximum thickness of 10 to 20 km. Hence the granitization processes appear at depths between 2 and 25 km.

The temperature of granitization, as discussed above, apparently approximates to 450° — 550°. Such temperatures, according to Rittman, Adams and v. Wolff (see Barth 1952, p. 8) are valid at depths of 15 to 20 km. In orogenic areas, during an orogeny, the necessary temperature may be already attained at 4 to 6 km.

The granitization process may take place anywhere in the earth's crust where a sufficient temperature prevails and where necessary materials for granitization are available. From field evidence it seems (p. 28) that at greater depths there first occurs granodioritization with extraction of potassium upwards from the most loaded (= pressed) places (Riecke's principle), a granodioritic composition being thus attained (if occurring within a sedimentary prism). At such depths, however, granodiorite composition may also be obtained by direct fractionation (Bowen), or by differentiation of mixtures of basaltic magma with secondary magmas (Daly), but, particularly at a depth of, let us say, 10 km or less, the prevalent temperature is far too low to fuse the rocks and to result in a molten magma.

According to Daly (1933, p. 185) »the main mass of the sial, down to the depth of at least 10 kilometers, has a composition which in most respects is intermediate between granite and granodiorite. Still deeper the mean composition of the sial, affected by load metamorphism and basic intrusions, as well as reflecting ancient magmatic differentiation, probably approximates to granodiorite».

In the upper levels of the sial still within the temperature range of granitization, during orogenies, a further extraction of potassium follows, caused by the pressure related to the folding and other orogenic movements, (Riecke's principle and a tendency to move from places of higher to those of lower energy (Ramberg, 1952)), then recurring in places of less stress (pressure), and there acting as agents for completing granitization, usually accompanied by silica migrating in the same direction. In such an environment, the migrating tendency of elements is towards the attainment of a granitic composition, as stressed by Hietanen-Makela (1953).

Also the migration of femic constituents, but in an opposite direction, has been supposed (Reynolds, 1946), there forming a »basic front». This may be quite possible and even probable, but hardly of any essential importance in the granitization process. Particularly within the areas of the Sula Mountains and Kangari Hills, where if any basification is to be explained as »basic front», it is of the very least importance compared with the whole.

Granitization as outlined above has been attributed to large scale occurrences. There may, however, be instances of granitization caused by occasional accumulations of heat energy in some limited area causing local granitization on a minor scale. In the latter processes a more intensive interchange of elements may take place than was suggested in the foregoing, and there may also even be features of a »basic front» which are more evident and essential. According to the recent work of Johannes and Winkler (1965), such behaviour of elements is even to be expected because if water acts as the transporting agent, and at a temperature of some 600° C, such elements as Mg tend to be removed towards higher temperature, that is, in the opposite direction to the migration of K, Na, Al, and Si.

Due to similar accumulations of heat, re-fusion of the rocks may also take place. Such a remelting would produce rocks with all the characteristics generally considered as being typical of magmatic rocks, as for instance the rocks at Keuruu (p. 15) and many quartz diorite bodies and veins found both in Finland and Sierra Leone.

In short, it has been suggested in the foregoing that under suitable conditions, the pre-existing sediments are transformed into gneisses and granodiorites which lose potassium and silica that elsewhere may cause granitization or form potash-rich rock bodies and veins. The related question is then, naturally, what happens during the granitization — or potash metasomatism — in addition to the possible converting of hornblende into biotite and the formation of microcline, to some extent at the expense of plagioclase.

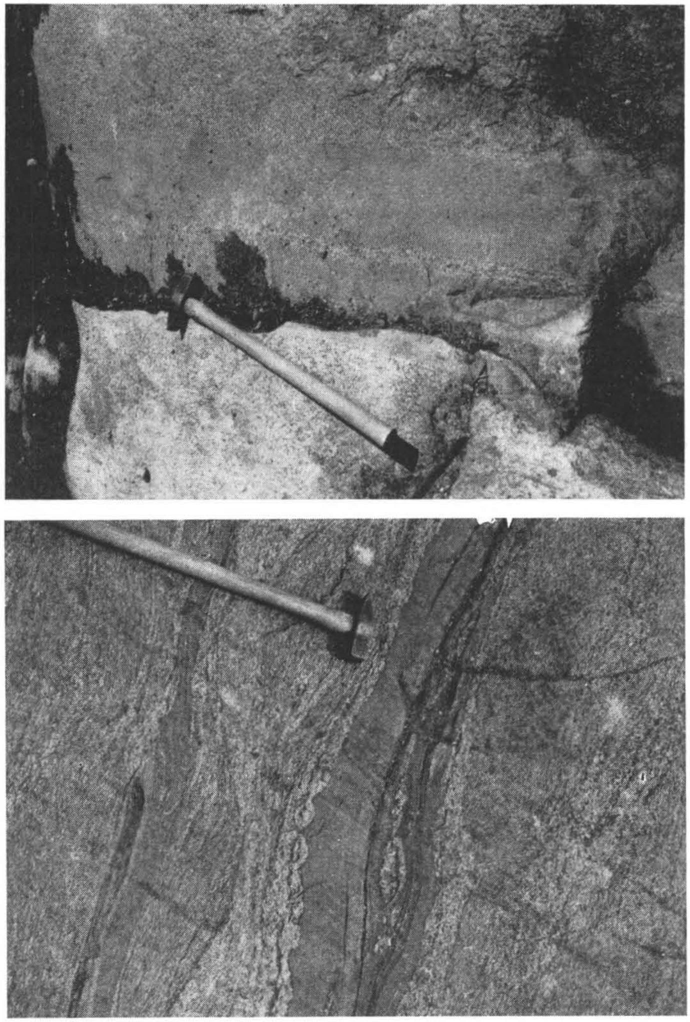
As mentioned above in several connections, the microcline of the synkinematic rocks is younger than the other constituents, and is either interstitial or fills the cracks and fissures or replaces plagioclase. The case of replacement, described by Seitsaari (1951) is typical of many synkinematic granodiorites (*op. cit.*, p. 98): »The best preserved crystals (of plagioclase) only contain sparse, tiny spots of microcline, but with advanced destruction the plagioclase is soon filled by complicating impregnation of microcline. With further replacement the microcline impregnations are united into a few larger, irregular crystals, finally forming one single crystal, which contains remainder of plagioclase. The end result is a pseudomorph of microcline after plagioclase, and no further growth of the microcline crystal has taken place».

Concerning the process of granitization many opinions and theories exist, and the possible divergencies between the theories presented are mainly the result of different views as to the origin of the potassium which caused the metasomatic changes.

Not to forget any one who has made a study of granitization I mention here my colleague Härme (1959). He takes as his starting point the fact that the granitizing material is derived from a granitic melt, and in this way explains also the Na:K ratio thereby produced. Furthermore, he agrees with the proposal of Wegmann (1935) that the addition of alkalies takes place at least in part as alkali aluminates, while admitting that the introduction of alkalies may also take place as silicates (Goldschmidt, 1920), which would probably be the case if the potassium derived from sediments (Marmo, 1958 a). Here it may be mentioned, that like many other ideas still much in favour for the explanation of many otherwise hardly understandable petrological problems, there is the old assumption, that alkalies are transformed together with alumina. 70 years ago Thugutt (1891, 1896) showed experimentally that during the hydrolysis of alumosilicates, part of the alumina passes into solution in the form of aluminates.

In his earlier paper, Härme (1958) points out that »basic front» has not actually been found in his examples, but that the amounts of Fe, Mg, and Ca still decrease during granitization. The present writer is not convinced of that because, in general, a replacement of Mg- and Fe-bearing minerals can very seldom be seen, but usually only of plagioclase, and even then the released Ca stays in the rock as epidote (Marmo, 1961 b). Mostly, however, the potassium introduced occurs as interstitial microcline without any singns of any kind of replacement. A very important observation by Härme is the fact that the Al-rich minerals have often been formed during the granitization, and this may also occur in connection with the replacement of anorthite by microcline, or — and this especially applies to the cases described by Härme — by locally observable biotitization of hornblende.

The opinion of the present author differs here from that of Härme mainly in that, instead of assuming a granite melt as the source of the granitizing potassium, the potassium derives, under hydrothermal conditions, from the sediments causing granitization elsewhere. In some cases, if examined locally only, both explanations may appear as correct. In Fig. 13 a spot of migmatite is shown. There is a compact vein of microcline aplite cutting a mica gneiss which at the vein seems to be enriched in microcline, the margins being diffuse. In the same figure (B) is another portion of the same migmatite showing very sharp margins between aplite and mica gneiss. The latter is the more common case. If we take it that the aplite is the source of granitization, the former, would indicate that the diffuse contacts are a result of



A

B

FIG. 13. Portions from a migmatite. A: Diffuse margins between aplitic vein and surrounding gneissic portion; B: Sharp contacts between amphibolitic strip and enclosing microcline-rich gneiss. Otaniemi, near Helsinki, Finland. Photo E. Halme.

progressive granitization caused by the vein aplite. On the other hand an exactly similar picture would be obtained if, at this particular spot, the accumulation of potassium extracted from the material were converted into mica gneiss and transported into opened space (lower free energy and necessary space) and then infilled the spaces like a veinlike formation. This view gains support if a somewhat larger area is examined: thereby it is seen that the contacts sharpen simultaneously with the narrowing

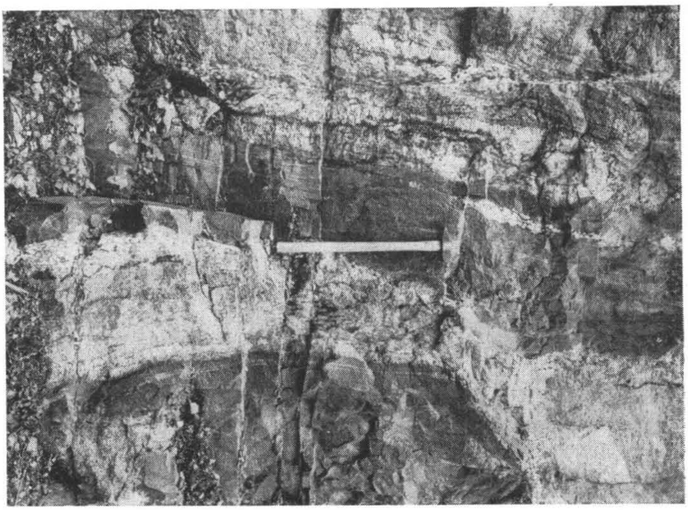


FIG. 14. Dark amphibolitic »interbeds» in a migmatite. The upper light portions are composed of »gneissose aplite», the gneissosity being a relic structure of very intensely granitized schist. The light portion below the hammer is more homogeneous aplite. Otaniemi, near Helsinki, Finland. Photo E. Halme.

of the aplite vein, resulting in aplite similar to that in Fig. 14. Furthermore, the microcline veinlets and grains around the veinlet with diffuse contacts are typical of zones on both sides of the veinlet much too broad for them to be explained reliably as caused by the aplite. In Fig. 14, where a similar aplite is migmatizing amphibolite (which itself could not supply any potassium), the margins are always very sharp. Furthermore, among apparently homogeneous mica gneisses which in southern Finland, according to Simonen (1953), are graywackes in origin, there are often patches richer in microcline than the surroundings. For instance, in quarries it is easy to notice that such patches are usually also restricted with the depth, and their shape may be irregular or lense like.

The distribution of additional potash feldspar occurs either as porphyroblasts or as interstitial or fissure infilling. Such patches may be explained if we assume that the potassium enriched into these patches and derived from other portions of the same sediment beds.

When describing local observations on the granitization of some rocks near Keuruu, Finland, Felici (1964) likewise reached the conclusion, that there the granitizing material has been (*op. cit.*, p. 14): »concentrated in an area of lower free energy - - - and its provenance is supposed to be metamorhosed old sediments and (acid) volcanic rocks».

The potash feldspar may thus be formed in yet another way. It may derive from other potassic minerals, which under metamorphic conditions become decomposed.

Nykänen (1961) has described gneisses from western Finland containing microcline, which, in his opinion, are the product of decomposition of micas into cordierite or sillimanite and potash feldspar.

If the accumulation of potassium takes place into open cracks and fissures, it may form — being transported silicates and aluminates — aplites, and the granitic material, under hydrothermal conditions, may then be transported long distances and thereby fill up fissures and veins of all possible sizes.

The discussion above may be epitomized as follows: The effect often observed in gneisses, migmatites, and also in acid plutonic rocks and described as granitization, is in most cases caused by potassium derived from other parts of the same rock, and removed into places of lower free energy. If cracks and fissures have formed, the same granitizing material reappears finally forming granitic, aplitic and pegmatitic veins.

The vice-versa granitization, that is, granitic material invading other rocks around aplitic and granitic bodies, is also possible but less common, because in this case the material has to penetrate rocks of higher free energy. Everybody has the experience, that it is easy to squeeze out juices for instance from an orange or soft concrete, but rather difficult to get them back without full destruction of once pressed material.

LATEKINEMATIC GRANITES

General

The latekinematic granites, as first defined by Eskola (1932) were emplaced in a late stage of orogeny (p. 9). They are usually pink and tend to be aplitic, and correspond to the granites of Sederholm's second (*e.g.* 1925) group. Later on, Eskola (1950) pointed out that the ideal granite composition is most common among the granites belonging to this group. The latekinematic granites are rarely gneissose. They are usually medium- to fine-grained, and they readily form migmatites with older rocks. Such granites have some characteristics in common with the disharmonious granites of Walton (1955), and they are identical with the serorogenic granites of Wahl (1936 a). They are probably also included by Saksela (1936) in his late-orogenic granites, as well as by Read (1948) in his intrusive granites. Simonen (1960, p. 64): »These potash-rich granites do not belong as an acid end member to the other plutonic rock provinces of the area, because a marked break occurs in mineralogical as well as in chemical composition between the potash granites and granodioritic end members of other plutonic rock provinces of the area. Microcline granites form a unique group without basic and intermediate members».

As already mentioned (p. 11), the duality of granites is accepted by the majority of those who have studied granites, as it has been from the early days of granite geology.

Daly (1933) considered, that the oldest »bottomless masses of granite batholiths» have been generated by anatexis, according to the theory of palingenesis; but the rise of voluminous granitic magmas during late Archean and subsequent time, he considers as a late member in the normal eruptive sequence from basic to acid.

Bowen and many other petrologists believed that all granites are magmatic. Against this point of view Daly wrote (*op. cit.*, p. 423): »- - - Richardson, like Bowen, does not approve of this conception of what may be called a double origin for the granites of the world, but to assume a single mode of origin is to plunge into difficulties». Still, 20 years later, Polkanov (1955 a) when discussing mainly granites here considered as late- and postkinematic, was against the widening of the granite-conception and concluded that the name granite should be used only for the rocks of undoubtedly magmatic origin.

The duality of granites was resolutely rejected in another way by the recent representatives of the French school, Perrin and Roubault, who expressed their

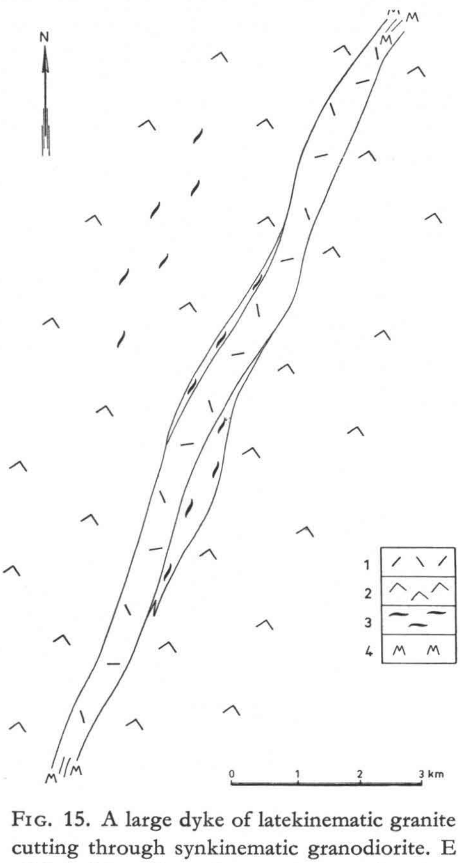


FIG. 15. A large dyke of latekinematic granite cutting through synkinematic granodiorite. E of Sula Mts., Sierra Leone. 1 = granite; 2 = granodiorite; 3 = gneiss; 4 = migmatite.

views in a rather categoric manner (1950, footnote on p. 91): »- - - we refuse, unless we obtain absolute proof to the contrary, to think that rocks with such an individual structure as the granites, have been formed, some from a state of magmatic fusion, and others by diffusion through solid rocks. Without proof we cannot agree that there are granites and granites. In our experience the granitic structure is characteristic of crystallization in the solid state concomitantly with chemical interchanges. We do not, however, deny the possibility that some granite may be formed by the direct recrystallization of solid rocks, such as lavas, although we have not personally observed any such examples».

In the field the latekinematic granites always occur cutting the older formations, including the synkinematic gneisses and granodiorites. They may form bosses and stocks of considerable size, or dykes varying from several kilometers to a few meters in width, or also as minute veinlets such as those typical of migmatites. None of these occurrences possesses chilled margins, the presence of which would indicate an intrusion of hot material into a cold environment. In Figs. 15 to 17 different bodies and veins composed of latekinematic granite are illustrated.

The distribution of the latekinematic granites is very irregular. In certain areas, as in southern Finland, they are conspicuously abundant, as are also the migmatites made up of older rocks and latekinematic granite. In Fig. 18 the distribution of the latekinematic granites in southern Finland, according to Simonen (1960), is illustrated. They are far more sparse in Central Finland. In Central Sierra Leone and the Ivory Coast they are rare (Fig. 19).

In the following, the occurrence of some minor bodies of the latekinematic granites will be briefly described, because such bodies usually display all contact relations more clearly than large bodies with contacts often to a large extent masked.

In Central Finland, at Pohjaslahti, there is a large dyke-like body of pink, fine-grained granite extending for 10 km in length and 1 km in width. Its side contacts are distinct and sharp, the granite cutting granodiorite and diorite, and in its central part probably also gabbro, inside of which narrow veins of similar granite occur. At its southern end, however, the contact is very indistinct where the granite has definitely granitized porphyroblastic granodiorite, grading and finally fading out into the nongranitized rock.

A similar dyke of the same size has been examined by the present author in Central Sierra Leone (Fig. 15) where it cuts gneiss and granodiorite and forms migmatites, as well as granitizing gneiss at the ends of the large granite dyke.

In Fig. 16 another form of a latekinematic granite body is represented. As will be pointed out later on in this paper, this boss is not made up entirely of granite, but large parts of it contain albite and minor amounts of epidote, the composition thus representing a »granodiorite of albite-epidote facies» in the sense of Ramberg (1952). This body terminates sharply at gneisses in the east, and at various rocks in the west, but at the ends of the boss-like body a very well defined interfingering with amphibolite in the south and with gneiss in the north occurs, and, as revealed by

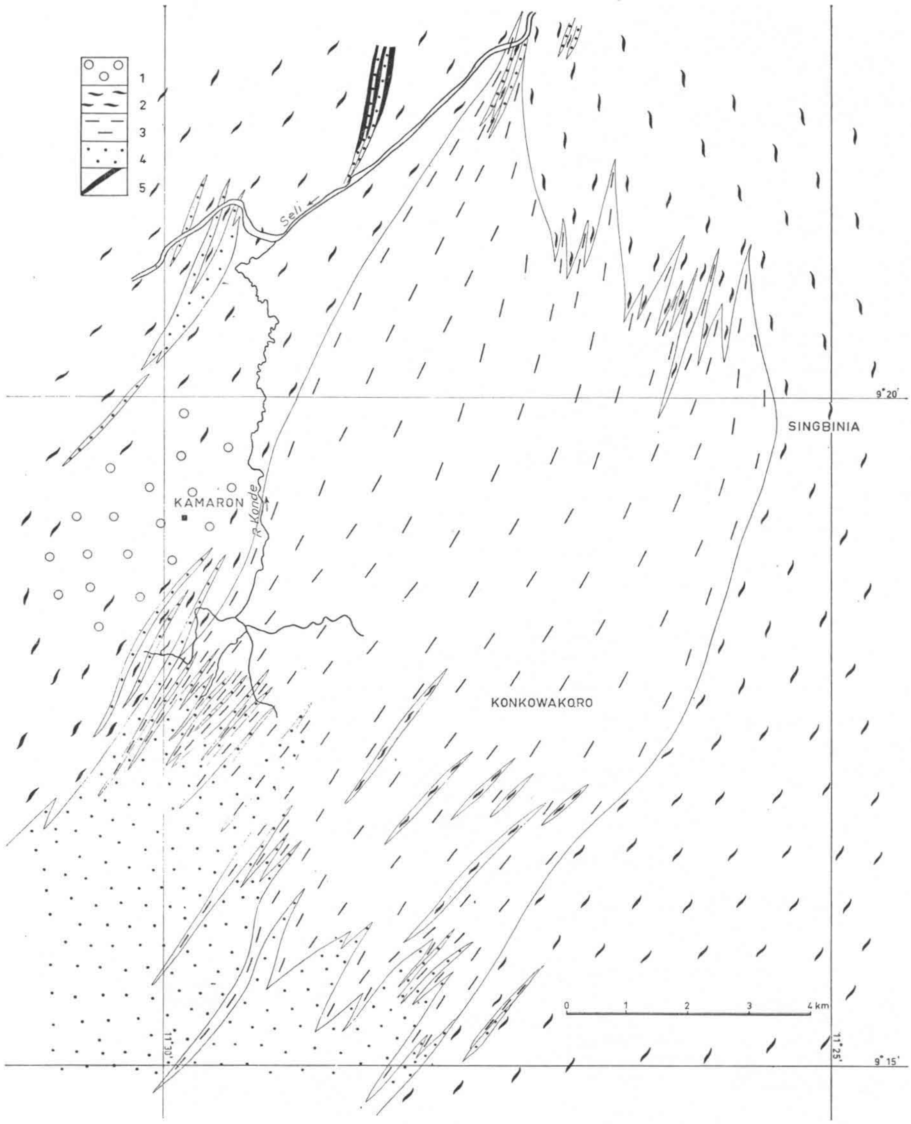


FIG. 16. Latekinematic granite at the northern end of the Sula Mts., Sierra Leone. 1 = porphyroblastic granodiorite; 2 = gneissose granodiorite; 3 = pink, latekinematic granite; 4 = amphibolite; 5 = magnetite-cummingtonite quartzite.

the geological maps, such a situation strongly supports an emplacement of the pink aplitic body from below through the strata causing a slight uplift of embracing rocks, resulting in an interfingering with the broken layering of strata at the ends of the body.

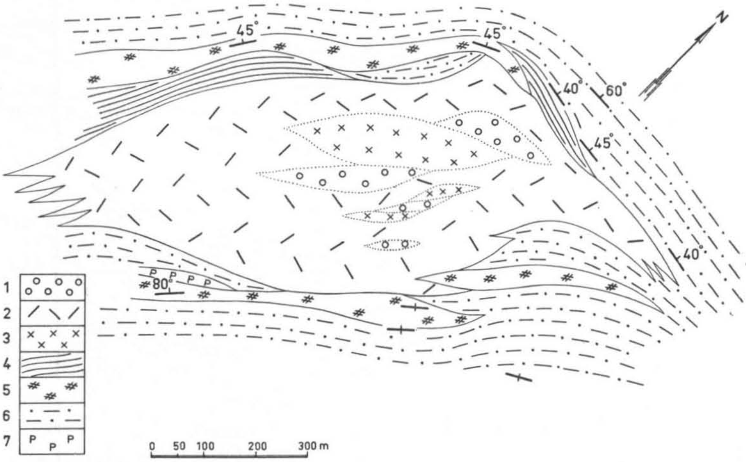


Fig. 17. Molybdenite-bearing latekinematic granite in the crest of a gente fold. Wankatane River, Sierra Leone. 1 = porphyroblastic granodiorite; 2 = latekinematic aplitic granite; 3 = latekinematic granite containing MoS_2; 4 = fine-grained gneiss; 5 = amphibolite; 6 = schist rich in talc and serpentine; 7 = pegmatite

Fig. 18. Distribution of latekinematic granites (solid black) in southern Finland, according to Simonen (1960, p. 65).

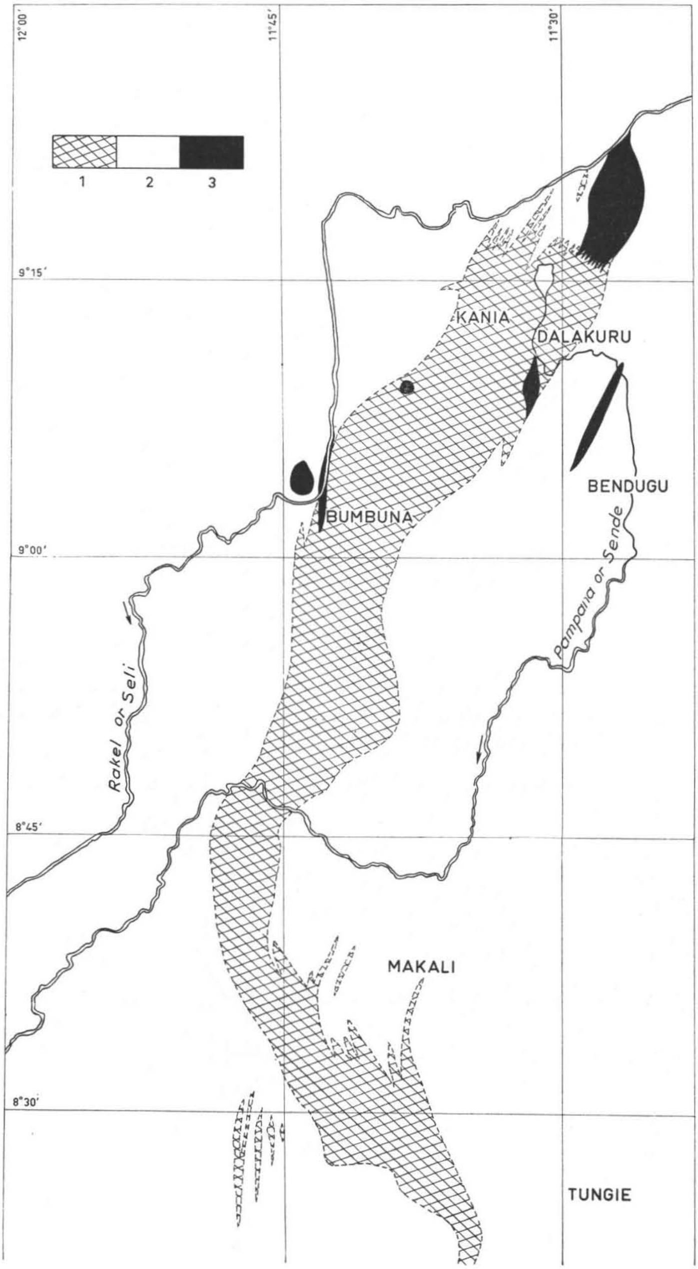


FIG. 19. Distribution of latekinematic granites in Central Sierra Leone. 1 = schist belt of the Sula Mts. and Kangari Hills; 2 = synkinematic rocks embracing the schist belt; 3 = latekinematic granite.

In Fig. 17 a molybdenite-bearing latekinematic, pink, aplitic granite is emplaced in a bend of the strata caused by a gentle fold. The side contacts are also sharp, but at the ends migmatization of the schists as well as short distance granitization together with locally observable interfingering occur.

The examples taken are typical of latekinematic granites, and they are all such, that anyone who believes that large granite bodies could granitize wide surroundings, would fail to find any proof for that from these bodies. On the contrary: all these granites have sharp long contacts, and only at their ends are effects of granitization visible. This should be kept in mind also in connection with what is written on p. 28 about granitization and granodioritization.

All bodies mentioned above may contain skialithic remnants, which are also conspicuous in the molybdenite-bearing granite body of Fig. 17.

In southern Finland, however, the latekinematic microcline granites contain many more of these ghost-like remnants and they may be sufficiently abundant to support the suggestion that such granites were formed entirely palingenetically, as was concluded by Sederholm (1912) and Eskola, or metasomatically, and that (Simonen, 1960, p. 65): »- - - in place of the present microcline granite there had earlier been another solid rock. The manner of occurrence of microcline granites follows old structural features of the pre-granitic rock crust». But Simonen also says, as a generalization, that the independent tectonic feature of such granites is that of a diapiric dome-like shape of the large areas occupied by latekinematic microcline granites. In such cases, the contamination of the intruding granitic material by the pre-existing material is obvious, and this may also be proved by the fact that in southern Finland such granites often contain garnet in abundance, or, as for instance south of the town of Jyväskylä, they contain many fine needles of sillimanite (Kulonpalo and Marmo, 1955). Furthermore, according to Härme (1960), the southern Finnish granites may also be fairly coarse, and sometimes pegmatite-like with skialithic inclusions in varying abundance, and sometimes they are cordierite-bearing.

Mineralogy of the latekinematic granites

The most typical mineralogical composition of the latekinematic granites is microcline — albite-rich plagioclase — quartz — biotite and/or muscovite. Mäkinen (1913) described a microcline granite with 49.0 % microcline, 26.1 % quartz, 20.8 % albite (An_5), 2.6 % muscovite and 1.5 % biotite. The variation in mineralogical composition of such granites is very small.

Microcline

It is well worth noting that the potash feldspar in the latekinematic granites so far studied by the present writer is exclusively microcline. Furthermore, as revealed by the texture of the rock, there usually do not appear to be any distinct age differences between different feldspars, rather the microcline and plagioclase seem to have been formed contemporaneously. Exceptionally, however, Cannon (1965) has described latekinematic granite with replacive relationship of microcline towards plagioclase (from British Guiana). As far as the triclinicity of the microcline of the latekinematic granites has been determined (Marmo, 1961; Marmo and Toini Mikkola, 1955; Marmo and Permingeat, 1957), it is always considerably high — 0.9 or more. Some additional examples from Finland: pink granite of Kemiö — 0.9; migmatizing granite, Otaniemi — 0.95; so-called Hetta granite from Finnish Lapland — 0.95. Values of 0.8, however, have been observed in an aplitic granite, possibly derived from rhyolitic meterial, in Central Finland (Marmo, 1961 a). Guitard and Lafitte (1959) report from the normal granite of the Pyrenees, with 33.4 % quartz, 24.4 % microcline and 34.7 % plagioclase, that there the triclinicity of microcline is constantly 0.8 to 0.9. The present writer has collected some samples of supposedly latekinematic granites from northern Cameroun. There the triclinicity of microcline turned out to be 0.9.

Another conspicuous feature of the microclines of the latekinematic granites is that they contain sodium in only very small amounts, or may even be almost void of it. Mäkinen (1913), however, has analyzed microcline of an albite aplite and of a microcline granite (Tammela area) finding 14.54 % K_2O — 1.26 % Na_2O and 14.11 % K_2O — 1.80 % Na_2O respectively. The low sodium content, on the other hand, is in agreement with the high triclinicity of potash feldspar.

Perthite may or may not be present. Most of the latekinematic granites examined by the writer contain microcline which is very weakly or nonperthitic. The intensely perthitic microclines are, on the other hand, typical of certain syenite and monzonite stocks, as well as of some granites characterized by unusual accessories (niobium and rare earths), which are also to be considered as latekinematic, but they are not common types among the rocks under consideration. One such body is at Tebo, Central Sierra Leone (Marmo, 1962), which contains perthitic microcline (Fig. 20), oligoclase and hornblende. But, as mentioned, this is not in any way typical of actual latekinematic granites, in general, and, if in the latter rocks perthite occurs, it is a microperthite and not the »hairperthite», which is the common form in the former syenites and especially in the rapakivi and Alpine granites, both to be considered as postkinematic. Unfortunately, in the literature dealing with granites of this kind the presence or absence of perthite has seldom been mentioned. Therefore the available examples are not very plentiful. The Sierra Leonean latekinematic granites do not usually contain any traces of perthite. In Finland, concerning the microcline granites of the Tampere area, Seitsaari (1951) remarks that the distinctly cross-hatched microcline is unaltered, and sometimes contains perthite streaks. Edelman (1956) pointed out that the microcline of the pink granites and aplites in the Archipelago of Southern Finland is clear, and perthite is not mentioned. A. Mikkola (1949), on the other hand, reports that in the latekinematic granites of the area north of the Gulf of Bothnia, perthite is common. Concerning the granites of Lapland, on the contrary,

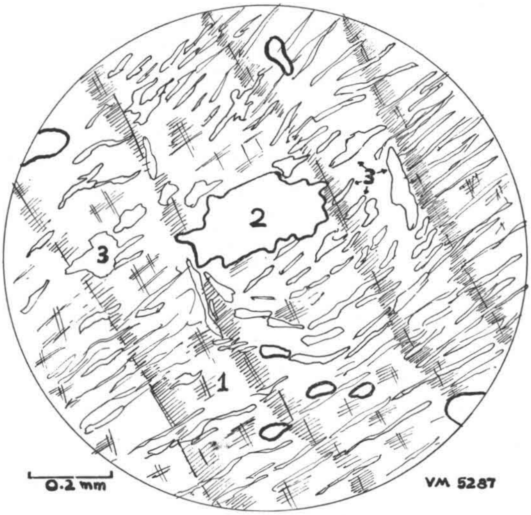


FIG. 20. Microcline crystal in a hornblende-bearing granite. Between Mano and Kenyema, Sierra Leone. 1 = microcline; 2 = quartz; 3 = plagioclase.

Erkki Mikkola (1941) did not mention perthite. According to Simonen (oral communication) the presence of perthite in the Finnish latekinematic granites is not any conspicuous feature. From a great number of thin sections of latekinematic granite from the area of Pihlajavesi, Central Finland, about two thirds contained weakly developed perthite, but one third did not contain it at all. The scarcity of perthite is to be expected, because it seems from all available data, that perthite is not common in the microclines of high triclinicity, and it should not occur if the content of sodium is low.

As mentioned, in the latekinematic granites, microcline is usually of more or less the same age the other major constituents. Sometimes, however, another and definitely younger generation of well cross-hatched microcline may occur simultaneously. As an example the granite of Kontozero (Kola peninsula) may be mentioned, which, according to Maslenikov and Priyatkina (1960) contains minute microcline veinlets crosscutting the larger grains of the constituents of the rock, including microcline. This later microcline also fills interstices and sometimes occurs along grain boundaries between quartz and plagioclase. The main texture of the rock is, however, typical of the latekinematic granites as described above.

Plagioclase

In the latekinematic granites, plagioclase tends to be albitic, as described by many students of the latekinematic granites in several connections. According to

Simonen (1960, p. 68), however, it is usually oligoclase, and »zonar texture has been found only as a rarity». In the microcline granite described by Mäkinen (1913), plagioclase is albite (An_5). According to A. Mikkola (1949) the three analyzed Karelidic latekinematic granites contain normative plagioclase with An_5 to An_{15}. In Central Finland, the latekinematic granites of the Pihlajavesi area contain plagioclase with An_{10} to An_{15}, in a few cases with less than An_{10}.

The latekinematic granites of Central Sierra Leone (Wilson and Marmo, 1958), contain albite or acid oligoclase with An-content varying from 2 to 15 %, in most cases from An_5 to An_{10}. When calculated from chemical analyses (Marmo, 1958 b), the normative plagioclase contains 2.2 to 16.9 % An. According to Wilkman (1931), the microcline granites of the map sheet C4, Kajaani, Finland, contain plagioclase with An_1 — An_{15}. In British Guiana (Cannon, 1965) the plagioclase of latekinematic granites is, on an average, An_8. The microcline:plagioclase ratio varies also, and, for instance, at Ylivieska, there is a granite with 40 % albite (An_7), 29 % quartz and 25.5 % microcline.

It may also be mentioned that Wahl (1936 a), when proposing his granite classification, gave as a criterion for his serorogenic granites that the ratio of K_2O to CaO should be more than 2, but usually more than 4, which means that plagioclase must be very acid.

This is opposed to the plagioclase of synkinematic granites with An_{25} — An_{30}, and also to that of postkinematic granites with more or less similar plagioclase. In synkinematic granites Wahl (1936 a) claims K_2O:CaO to be less than 1.

Furthermore, in the latekinematic granites the plagioclase forms crystals which are usually well separated besides the microcline occuring in a similar way. In most of the cases examined both feldspars seem to be of the same age. This is not the case in synkinematic granites, where microcline is always and distinctly younger than plagioclase.

It is of especial interest to note that the composition of plagioclase mainly encountered in the latekinematic granites varies between An_5 and An_{15}. This is the range, which according to recent observations falls into the category of peristeritic plagioclases (see e.g. Laves, 1954; Ribbe, 1962) in which a low temperature unmixing into components An_2 and An_{22} has often been observed as directional schiller. Unfortunately, there are very few, if any, investigations on the plagioclase of latekinematic granites from this point of view. Therefore this fact can only be pointed out here refraining from any conclusions. In the future, however, more detailed study of plagioclase of respective composition may be of much importance for the understanding also of genetical questions concerning these particular granites. According to Christie (1959), below a certain temperature, diffusion of Al and Si within the plagioclase would be so slow that the formation of peristerites is negligible even during geological time. How common is the peristerite in the latekinematic granites? This is a very interesting question which will be examined.

Epidote

In general, epidote is uncommon or a sparse constituent in the latekinematic granites. Sometimes, however, it may be present in conspicuous quantities, and, as a matter of fact, the epidote granites are to be considered as an important and interesting group among the latekinematic granites.

A good example of such a granite is the boss at the northern end of the Sula Mountains, Sierra Leone (Wilson and Marmo, 1958) which contains irregularly distributed epidote in very varying amounts. In this boss, the rock is a true microcline granite only to a certain extent, for there are also areas occupied by an epidote-albite-rich rock, which should preferably be termed an albite-epidote granodiorite.

In the potassium-rich varieties, the amount of epidote is less than 2 %, and usually does not exceed 1 %. In those varieties which contain more sodium than potassium, on the contrary, the epidote-content is higher, and may be exceptionally as high as 10 % in volume. But still, despite the Ca-content of epidote, if the normative plagioclase is calculated from the bulk composition of an epidote-bearing granite the anorthite-content remains in most cases below 15 %, and in one particular case with 6 % epidote the normative plagioclase contains only 16.9 % An. In a sample with 2.0 % modal epidote, the An-content of normative plagioclase remains as low as 2.2 %, and the rock contains 0.69 % Ca, 4.08 % Na_2O and 4.81 % K_2O, thus approaching an albite-epidote granodiorite in composition.

Such epidote-rich rocks actually approach the helsinkites of Laitakari (1918) with up to 35 % epidote, and only 0.19 to 1.90 % K_2O, the plagioclase being albite. Ramberg (1952) considers such rocks to be the best representatives of the amphibolite-epidote facies within the gneiss-granite rocks.

But the Sierra Leonean rocks which are richest in epidote, are still closer to the unakites of Finland, which, according to Wilkman (1931), contain albite, Fe-rich epidote, chlorite, microcline, and quartz as the main constituents. The microcline, which is always very pure, is somewhat older or of the same age as the albite. In four chemical analyses published by him, the lime- and alkali-contents are as follows:

CaO	3.98	4.30	1.93	10.10
Na_2O	7.94	7.63	5.23	4.44
K_2O	1.90	1.16	7.74	2.62

The most conspicuous difference between these unakites and the epidote granites of Sierra Leone is the much higher lime-content of the former rocks.

The relationship between the ordinary microcline granites, and the epidote-rich varietes and epidote-albite rocks will not be discussed separately. Here the origin of epidote is of particular interest.

The epidote of helsinkite and unakite is rich in Fe_2O_3. This is reflected in the bulk composition of the unakite rocks as well, the chemical analyses showing Fe_2O_3-contents up to 3.58 %, 5.11 % and 6.03 %. In such rocks, the epidote has been considered both by Laitakari (1918) and by Wilkman (1931) as a primarily crystallized constituent, formed under conditions of comparatively low temperature of emplacement and by the presence of water. In the case of the epidote-bearing latekinematic granites of Sierra Leone, however, the epidote is mostly low in iron. Therefore a similar explanation cannot be accepted without important reservations. These epidote-albite rocks are more like those described by Kranck (1931) which occur in connection with migmatites and pegmatites. He regarded the »helsinkites» as being the products of autometasomatism. Seitsaari (1951), on the other hand, believes that the epidotization has been caused by potash metasomatism and subsequent secondary mobilization of the constituents of plagioclase.

In the helsinkites and unakites, the epidote is definitely iron-rich. Such an epidote cannot be formed merely through alteration, because the anorthite of plagioclase cannot produce, without introduction of iron, such an epidote, and introduction of Fe is not very likely there. This is not always the case if the latekinematic epidote-granites of Sierra Leone are considered. There are some varieties (shortest in potassium) which contain 1.9 to 2.2 % Fe_2O_3, and the epidote may likewise be iron-bearing and primarily crystallized. In the majority of cases examined, however, the iron-content in general, and Fe_2O_3 in particular, is low: on an average 0.3—0.5 % FeO and 0.3 % Fe_2O_3. Furthermore, in these rocks the metasomatic origin of epidote can often be clearly seen in thin sections.

Barth (1952) considers epidote to have formed through the process of saussuritization of anorthite, either in connection with potash metasomatism and accompanied by the formation of muscovite:

$$(1)\quad \underset{\text{anorthite}}{4CaAl_2Si_2O_8} + \underset{\text{orthoclase}}{KAlSi_3O_8} + \underset{\text{water}}{H_2O} \rightarrow$$

$$\underset{\text{zoisite}}{2Ca_2Al_3Si_3O_{12}OH} + \underset{\text{muscovite}}{KAl_3Si_3O_{10}OH} + \underset{\text{quartz}}{2SiO_2}$$

or by the introduction of lime:

$$(2)\quad \underset{\text{anorthite}}{3CaAl_2Si_2O_8} + \underset{\text{lime}}{Ca(OH)_2} \rightarrow \underset{\text{zoisite}}{2Ca_2Al_3Si_3O_{12}OH}$$

The alternative (1) seems to explain the formation of epidote of the granite here under consideration. The granites always contain potassium in excess, appearing in the young interstitial microcline. Also biotite is very sparse or lacking, muscovite being the only mica in most instances, which also indicates the introduction of potassium. Hence the epidote is here a product of granitization at the expense of anorthite, which adequately explains the fact that the plagioclase in these granites is usually or nearly albitic. Fig. 21 illustrates a granite porphyry showing strong saussuritization

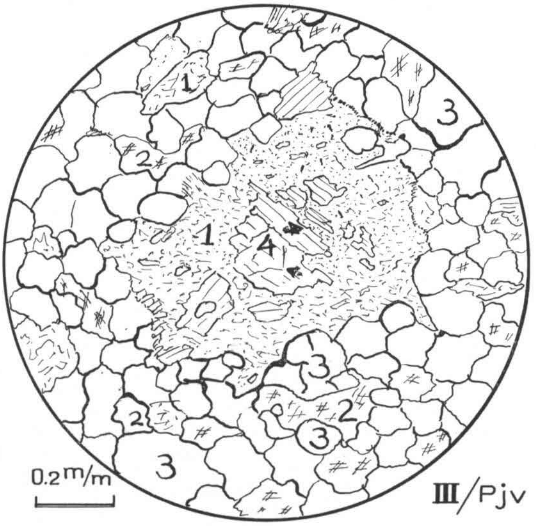


FIG. 21. Sericitic plagioclase inset in granite porphyry. Pihlajavesi, Finland. 1 = sericitic plagioclase; 2 = microcline; 3 = quartz; 4 = muscovite.

of the plagioclase insets, often resulting in real pseudomorphs after plagioclase, composed of fine, compact grains of epidote. Analogous features are often observed also in the latekinematic epidote granite, and there is no doubt that the epidote was formed at the expense of the anorthite of the plagioclase. In addition to epidote, such pseudomorphs always contain tiny scales of muscovite (sericite) and small grains of quartz, thus representing a »chemical reaction written in stone».

A somewhat different kind of origin for epidote may be seen in other cases, where epidote and hornblende occur in close association with sphene, which is usually not very common in the latekinematic granites, and also with small rounded grains of apatite. Sometimes biotite is sparse, but in other instances it may completely replace the hornblende. In such cases, that is, when epidote and hornblende or biotite are associated, the biotite seems to be more abundant than in the latekinematic granites in general. The association epidote — biotite is well illustrated in many synkinematic granites as well.

It may be suggested that the generation of epidote from hornblende arises from the following reaction:

(3) $$2\ \underset{\text{hornblende}}{2CaO \cdot 3(Mg,Fe)O \cdot 2Al_2O_3 \cdot 6SiO_2 \cdot H_2O} + 2KOH \rightarrow$$

$$\underset{\text{biotite}}{K_2O \cdot 6(Mg,Fe)O \cdot Al_2O_3 \cdot 6SiO_2 \cdot 2H_2O} + \underset{\text{zoisite}}{4CaO \cdot 3Al_2O_3 \cdot 6SiO_2 \cdot H_2O}$$

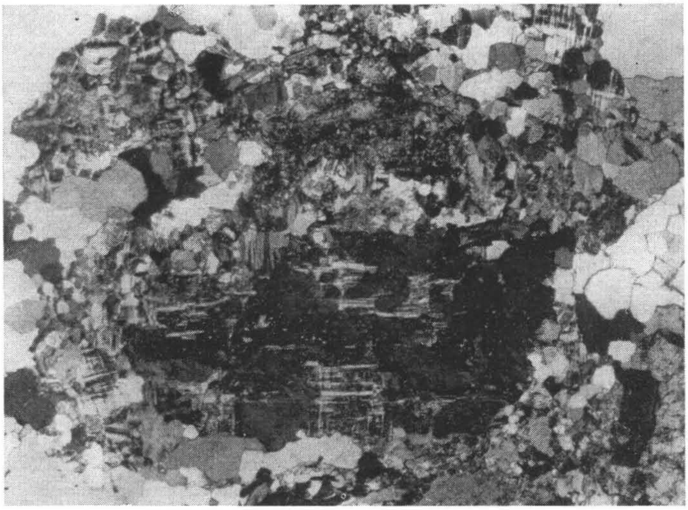


FIG. 22. Microcline replacing sericitic plagioclase in granodiorite. Pihlajavesi, Finland. N +, magn. 25 x.

The equation is, however, only an approximate one, because the Ti of hornblende also uses some lime and silica for the formation of sphene. Such an alteration necessitates the introduction of potassium. If it happens without potassium, evidently biotite will be absent from the final reaction product.

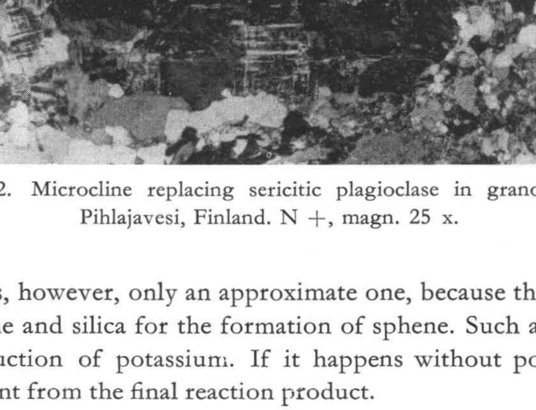


FIG. 23. Microcline replacing plagioclase in a synkinematic granite. At the upper end of the latter there is younger and perfectly fresh albite. South of the Kangari Hills, Sierra Leone. Magn. 40 x.

(4) $2\ 2CaO \cdot 3(Mg,Fe)O \cdot 2Al_2O_3 \cdot 6SiO_2 \cdot H_2O + H_2O \rightarrow$
hornblende water

$4CaO \cdot 3Al_2O_3 \cdot 6SiO_2 \cdot H_2O + 6MgO \cdot Al_2O_3 \cdot 3SiO_2 \cdot 2H_2O + 3SiO_2$
zoisite aluminous serpentine quartz

As a matter of fact, the hornblende associated with epidote is frequently surrounded by a narrow rim of chloritic material.

Also direct hydrolysis of anorthite must be considered as a source of epidote.

(5) $$4(CaO \cdot Al_2O_3 \cdot 2SiO_2) + 7H_2O \rightarrow$$
$$4CaO \cdot 3Al_2O_3 \cdot 6SiO_2 \cdot H_2O + 2SiO_2 + 2Al(OH)_3$$

Eskola (1934) considered this mode of formation of epidote to be the most likely when he discussed the »helsinkitization» by purely autohydrothermal alteration of the Baltic porphyries. The released alumina and silica may then react with introduced potassium to form either potash feldspar or muscovite.

According to Ramberg (1943) the An-content of the plagioclase in equilibrium with epidote under moderate water pressure would decrease with falling temperature. This is in agreement with petrological observations concerning, *e.g.* Sierra Leonean epidote-bearing latekinematic granites. It is also to be pointed out, that plagioclase, before epidotization (see p. 45), has evidently been peristeritic, which, according to Christie (1959) would also fascilitate the formation of epidote.

Grant (1953) believes that the fact that the PT conditions of certain granites are those of amphibolite-epidote facies, while those of the surrounding country rock are of amphibolite facies, is due to the intrusion of such granites after the maximum metamorphism.

The present author would add that the emplacement of the latekinematic granites took place under hydrothermal conditions and in the presence of abundant water, which forced the mineral association towards what is generally believed to correspond to a lower stage of metamorphism than that of the surrounding country rock (including synkinematic granites).

POSTKINEMATIC GRANITES

Rapakivi

Among the postkinematic granites, as defined on p. 9, both microcline and orthoclase granites occur, although the latter are very unusual, and may even be absent among the latekinematic granites.

In Fennoscandia, Sederholm classed the postkinematic microcline granites with his third group of granites, together with the latekinematic ones. Simonen (1948 a) however, pointed out that there are microcline granites penetrating the migmatite-forming granites in southwestern Finland, thus belonging to the postkinematic intrusions of the Svecofennidic orogeny. These granites (according to Simonen) include those of Obbnäs (Sederholm, 1926), Onas (Hackman, 1905), Lemland (Sederholm, 1934), Åva (Sederholm, 1924; Kaitaro, 1953) *etc.*, and petrochemically they deviate only slightly from the latekinematic granites, mainly being richer in silica, alumina and potassium (Simonen, 1948).

According to Eskola (1955), among the Precambrian postkinematic granites rapakivi is the most typical representative. This granite contains abundant strongly perthitic orthoclase, this form of potash feldspar being preponderant over microcline in these rocks. Eskola held this granite as characteristically magmatic, comparing it, tectonically, with the »disharmonious granites» of Walton (1955).

In one of his earlier papers, Eskola (1950, p. 7) wrote: »The rapakivi retains its typical structure up to the very contact and even in the breccia, showing that tranquility of structure which is characteristic of the rapakivi, with no signs of the movement that is so striklingly manifested in the breccia. The rapakivi must have crystallized exactly at the place it now occupies. It is a postkinematic pluton». Savolahti (1956) points out that the crystallization started in rapakivi with the potash feldspar and quartz, and that the younger rock types of the same intrusion are richer in plagioclase and mafic minerals. Tuttle and Bowen (1958, p. 93): »To many petrographers the name rapakivi has come to signify granite in which potassium feldspar is mantled, part at least, by plagioclase feldspar (usually oligoclase). This restriction of the term is unfortunate as many geologists include under the classification of rapakivi granites which do not carry mantled alkali feldspar». This definition of a rapakivi is, however, both incorrect and misleading, because a similarly mantled potash feldspar occurs in some synkinematic porphyroblastic granites, as, for instance, certain granites of Central Finland, which have nothing to do with the rapakivi. But there is another characteristic, in addition to the mantled ovoids, which is especially typical of a rapakivi: The potash feldspar of the rapakivi granites is predominantly orthoclase, entirely absent or uncommon in the Precambrian syn- and latekinematic granites. This is true not only for the rapakivi of Finland, but also for similar rocks of the Ukraine and the Urals. Also the rapakivi of Brazil (Goni, 1961) contains orthoclase which, as well as microcline, is usually enveloped in an oliogoclase ovoid. In all the instances mentioned, the orthoclase is conspicuously perthitic, of very non-homogeneous triclinicity, and commonly contains patches of cross-hatched microcline. Furthermore, microcline, usually younger than orthoclase, always occurs, but in subordinate amounts, and forms interstitial or fissure infilling. This microcline is mostly of high triclinicity. Stewart (1959), however, has described the rapakivi of Penobscot Bay, Maine, which does not contain orthoclase but only microcline. From his description it may be seen, however, that even this microcline is of a very poor triclinicity: in most cases it is less than 0.70, and often 0.27 to 0.50. It is also rich in albite, the Or-content varying between 55.6 and 73.8 %, thus also in this sense differing from actual rapakivi granites in which plagioclase is oligoclase.

It may also be mentioned here, that the nature of the potash feldspar of the rapakivi granites is entirely unknown among the products of granitization or in any granites which could possibly be explained as metasomatic and as products of some other rocks. This fact was probably missed by Backlund (1938) when he tried to explain the rapakivi as a granitization product derived from Jotnian sandstone. Also Sato (1961) probably did not think of this kind of potash feldspar when he supported the views of Backlund on a petrochemical basis. Goni (1961), too, gave his support to a similar explanation for the origin of rapakivi.

Against such an explanation is also the perfectly intrusive character of rapakivi, its varieties displaying intercutting phenomenon and the contact breccias in which the rapakivi is brecciating the older rocks belonging to the basement.

Alpine granites

The Alpine postkinematic granites (Eskola, 1932) are also orthoclase granites. Such granites have been described for instance by Gysin (1948, 1956) from the Alps and from the Himalayas, and by Marmo and Permingeat (1957) from Azegour, Morocco. They occur in the Andes, and they have been found also in the Central Urals. The orthoclase of these granites is very similar to that of the rapakivi, except that it does not form any large insets, but megascopically the rocks bear a strong resemblance to an ordinary microcline aplite. Furthermore, it may be mentioned that the Tertiary granite of Skye likewise contains non-homogeneously triclinic and very perthitic potash feldspar. According to Tuttle (1952) the potash feldspar there is mostly coarse perthite or orthoclase cryptoperthite, and the homogeneous material ranges from orthoclase to sanidine.

Among the postkinematic granites, however, true microcline granites occur as well. They contain only very intensely perthitic microcline and plagioclase which, when it occurs as separate grains, is oligoclase with up to 30 % An. One of such granites is that of Obbnäs (Sederholm 1926) which forms a large body in southern Finland clearly cutting all the other rocks. Härme (1959) has described its contact phenomena with clear granitizing effects. According to Laitala (1961), its feldspar is predominantly perthite, and one of his modal analyses, for Finnå granite, indicates: 66.2 % perthite, 32.5 % quartz, 0.9 % biotite, 0.4 % fluorite. Such a composition agrees well with an origin from a melt.

Within all the areas mentioned occupied by the orthoclase-bearing granites, other granites or aplites always occur which are still younger — hence also postkinematic — but which do not contain any orthoclase, the potash feldspar being there well cross-hatched microcline of conspicuously good triclinicity. Such aplites form veins cutting the rapakivi granites both in Finland and the Ukraine, and they are common within the Alpine granites. Marmo and Permingeat (1957) have described in detail veins of this sort from Azegour, Morocco, where such veins vary considerably in width, ranging from a few millimeters to several meters. As mentioned, they are pure microcline granites cutting the orthoclase granites with sharp contacts.

Riebeckite- and related granites

At several places so called riebeckite granites occur, which are characterized by the presence of riebeckite, arfvedsonite, aegirine *etc.*, meaning chemically that they contain more than usual ferric iron, especially in the silicate minerals. Sometimes such granites are closely associated with occurrences of tin and niobium minerals. Especially, the occurence of such granites in Northern Nigeria (Jos Plateau) has been well examined but they have been described in many other places, as well.

The feldspar of such granites is often »single feldspar», orthoclase perthite or anorthoclase. The presence of fluor-bearing minerals, such as topaz and fluorite is a typical feature of these granites. According to Turner (1963) the younger riebeckite granites in Nigeria are homogeneous but usually are chilled near the contacts. As mentioned above, the perthite forms there the entire feldspar content of the rock. The coloured minerals include fayalite, pyroxene, hornblende, riebeckite-arfvedsonite and biotite. The form of the intrusions is crescentic. These granites have been intruded later by albite-biotite granites which have almost circular outcrops, and contain besides perthite, also separate grains of albite.

Belonging to the same zone as the younger granites of Nigeria, are also similar granites in Niger. They are likewise tin-bearing, often greisenized and albitized along the margin. As a reference for these granites the granite of Tarraouadji, described by Fabriés and Rocci (1965) may be mentioned.

Barbeau and Géze (1957) have described a Quaternary granite from Tschad, Fort Lamy, which according to the authors is very similar to the »younger granites» of Nigeria. This granite has probably a very close connection with the rhyolite occupying the stratigraphically higher levels. According to the authors, the granite and rhyolite must be considered there as co-magmatic.

Venkataraman, Sen Sharma and Xavier (1964) have described similar granite from Rajahstan, India, containing 45 per cent by volume highly perthitic alkali-feldspar classified as single feldspar, and a few discrete plagioclase grains 1—6 per cent by volume, and interstitial quartz. Furthermore, the granite contains riebeckite and aegirine, sometimes intimately intergrown. The rock contains 0.09—0.20 per cent ZrO_2, but the contents of MgO and CaO are consistently low. Plagioclase is albite or acid oligoclase.

On the fluorine-content of granites

Discussion of the petrological significance of the peculiar mineralogy of these granites would be of utmost interest, and attempts along these lines have been made (for instance Fabriés and Rocci, 1965). This discussion, however, is probably premature, because our knowledge and understanding of the genetical conditions for amphiboles, niobates, *etc.* is still limited. There is, however, one point, which probably deserves special attention, and that is the fluorine, which has often been taken as accounting for the mobility of granites. The presence of this element is characteristic of most postkinematic granites — rapakivi, many Alpine granites, Nigerian granites, *etc.* But it is also sometimes present in certain latekinematic microcline granites, as, for instance, the granite of Otamäki, Finland. There is, however, a remarkable difference: in the last-mentioned and some other microcline-granites the fluorine occurs as fluorite, topaz not having been met with; in the orthoclase-bearing postkinematic granites, the topaz is characteristically present, occurring sometimes as conspicuously large crystals. It is often present in rapakivi but especially in the Nigerian »younger granites» and in particular in their greisenized zones and portions.

Petrochemically the introduction of fluorine into a granitic rock would always be able to generate topaz: $Al_2(F,OH)_2SiO_7$, because the amount of fluorine present needs a comparatively small surplus of Al_2O_3 to form this mineral instead of fluorite, CaF_2, which requires a similar surplus of CaO. On the other hand, in the microcline granites, the plagioclase is mostly albite, but in the orthoclase-bearing granites usually oligoclase. Thus one could tentatively suggest, that the lower temperature of formation of a microcline-albite granite yields, if fluorine is present, only fluorite, but, if the temperature of formation is elevated and suitable for formation of single K-Na-feldspar or of an assemblage orthoclase + oligoclase, the fluorine is able to form topaz. However, at the present stage of our knowledge, this must be considered merely as a suggestion.

On the accessories

Especially the granites containing riebeckite or aegirine, or both, or which are related to them, often albitized, are mostly characterized by accessory constituents not normally occurring in granites in general. Such constituents may be Nb_2O_5, lantanides, *etc.* Various authors have postulated for these accessory constituents that they are hidden in the lattices of other minerals, for instance in sphene. Modern techniques and new methods have fascilitated a closer study of these questions, and revealed, that these elements are not always dispersed but that they tend to form independent minerals. Examples of such studies are numerous, some of them having been already discussed in the present paper. Two more cases may still be mentioned here. At Honkamäki, Finland, there is a granite, areally closely related to the magnetite-ilmenite ore deposit, which contains, besides fluorine, also more Nb_2O_5 + RbO than usual (Marmo *et al.* 1966). The latter is definitely incorporated into lattices of microcline and biotite, the former, however, occuring as a mineral of the columbite-samarskite series. Also when in sphene, it forms minute but independent mineral inclusions. Lantanides form bastnäsite, ThO_2 thorite, *etc.* Gross and Heinrich (1965) have described granites from the Mount Rosa area, Colorado, where they found, in addition to fluorite, also anatase, monazite, bastnäsite, allanite and astrophyllite, which are also well known in the younger granites of Nigeria. All these findings are very interesting from the point of view of granite petrology. At present it seems that such accessories may be characteristic of a certain restricted group of granites only. This would mean that granites should also be classified on such a basis before making any decisions about the origin of granites themselves, and especially where the source of the granite-forming material is concerned.

THE GRANITE PROBLEM

General

As is shown in the description of the synkinematic rocks, the quartz diorite predominates over the granodiorite, and a granite composition is comparatively seldom to be found. Furthermore, it has also been revealed that the potash feldspar, which is almost invariably well cross-hatched microcline of high triclinicity, is younger than the other constituents of the rocks, and occurs in interstices or as fissure infilling (Fig. 6). Thus it seems that the potash feldspar, if it yields a granite composition, is metasomatically introduced in an overwhelming number of the cases examined.

The situation is entirely different in the late- and postkinematic granites, in which it is diffcult to discern any noticeable age difference between the potash feldspar, plagioclase and quartz. In fact, this becomes clear from the study of the radiogenic K/A ages of feldspar and micas extracted from granitic rocks (Marmo, 1960 a): In the synkinematic rocks of the Precambrian of Finland the mica ages are regularly some 300—350 m.y. higher than those of microcline, the former being around 1 800 m.y., and the latter about 1 500 m.y. When the ages of the respective minerals extracted from late- and postkinematic granites are considered, we may note that the ages for micas and potash feldspar are closely approximate. The same applies to the granites of the Ukraine (Polevaja, 1956):

	bulk sample	mica	potash feldspar
Plagioclase granite, Saksagan	2 000x10^6	1 970x10^6	2 050x10^6
Granite, Kirovograd	1 760x10^6	1 800x10^6	1 790x10^6
Rapakivi, Korsun	1 640x10^6	1 590x10^6	1 500x10^6

For the rapakivi granite of the Viipuri area (Polkanov, 1955) the following K/A-ages have been determined:

Rapakivi, bulk sample	1 440x10^6
Orthoclase ovoids of rapakivi	1 420, 1 400, 1 360x10^6
Graphic feldspar of rapakivi pegmatite	1 400x10^6
Mica of rapakivi pegmatite	1 500x10^6

But, in addition, there are young veinlets of microcline in rapakivi, which have an age of 1 180 x 10^6. Exactly the same age has been obtained for the microcline extracted from the aplite cutting the rapakivi.

These observations of the K/A ages well support the views based on the petrologically observed relative ages of potash feldspar and other constituents in different groups of granites. Furthermore, the typically granitic composition is characteristic of late- and postkinematic, but not of synkinematic rocks. Therefore, in the opinion of the present author, to deal with the actual granite problem itself one needs only to consider the late- and postkinematic granites, which have a texture common among the magmatic rocks, and both of which are often seen, in the field, as intrusive bodies. The latekinematic granites, however, have an additional characteristic. In the Precambrian rocks, they very frequently form migmatites with the older rocks. This fact and the absolute age relations of the feldspar and micas extracted from different granitic rocks has led to the conclusion that for instance in the Precambrian Russian shield (which, according to the diamond drilling records, is the basement of the younger sediments at present covering the plateau of Central European Russia), the potash metasomatism followed some 300 m.y. later than the regional metamorphism, presumably at the latekinematic stage of the orogenic evolution.

Once more it should also be pointed out that, in the Precambrian areas, within a single area full »differentiation series» from peridotite to granodiorite may exist. But then there is no petrochemical continuity from granodiorite to microcline granite, which itself is conspicuously homogeneous in composition.

As was mentioned on p. 46, however, a »series» within the latekinematic granites themselves may still sometimes occur, but then there is a sequence, also within the same body (Sierra Leonean latekinematic bodies or some unakites in Finland), from an albite-epidote rock through albite-epidote granodiorite to epidote-bearing microcline granite. Mostly, however, such sequences do not exist, but the microcline-albite granite forms a fairly homogeneous mass.

The assembly of potash feldspar with albite

As mentioned above (p. 42—45), the typical latekinematic granites of Finland and Sierra Leone consist of well defined grains of microcline and mostly albitic plagioclase (An_5—An_{15}), quartz, and only minor amounts of micas. The microcline is usually well cross-hatched and perthite is uncommon, and where it occurs it is coarse. On an average, the latekinematic granites are conspicuously rich in potassium. Three typical latekinematic granites of Finland (Eskola, 1956), those of Nattanen, Perniö and Hanko, contain respectively 3.34 %, 2.42 % and 2.25 % Na_2O, 1.10 %, 1.00 % and 1.59 % CaO, but as much as 5.00 %, 6.53 % and 5.85 % K_2O. According to Simonen (1960) an average of analyses of latekinematic granites gives: 1.14 % CaO, 2.78 % Na_2O and 6.07 % K_2O. In the study by Parras (1958) an average of 12 analyses results in the contents: 1.06 % CaO, 3.27 % Na_2O and 5.10 % K_2O. The molybdenite-bearing aplites and alaskites are still richer in potassium (Kulonpalo and Marmo, 1955):

	CaO	Na_2O	K_2O
Pink granite, Mätäsvaara	0.21 %	2.73 %	5.58 %
Molybdenite aplite, Muuratsalo	0.18 %	0.68 %	4.55 %
Molybdenite aplite, Ackley City Newfoundland	0.54 %	1.92 %	6.43 %

The granite of Raon-l'Etape, Vosges (Nicolas, 1961), which cuts the Devonian tuffs, contains 1.10 % Ca, 3.90 % Na_2O, and 5.05 % K_2O, or as minerals 54.4 % orthoclase with faint signs of beginning triclinicity, 32.8 % quartz, and only 7.5 % plagioclase with 7 % An.

It may already be mentioned here that the average composition of rapakivi is also high in potassium, but the plagioclase is richer in An-component.

Furthermore, several modal analyses of the latekinematic microcline granites exist, all of which indicate the richness of such granites in potassium. On p. 40, granite of South Finland with 49 % microcline and 20.8 % albite (An_5) was mentioned. Similar relationships between microcline and albite are common within Finnish latekinematic granites. According to Simonen (1960), microcline is the predominant salic constituent of microcline granites, and its content is 30 to 40 %; in plagioclase it is, on an average, 25—29 %. Such a composition was called by Eskola (1950), an »ideal granite» composition, which, however, does not correspond to the eutectoid granite composition, viz. the minimum-melting mixture in the resp. system (Bowen, 1954), which contains almost equal amounts of soda and potash feldspars, these as established by experimental investigation. Also such granites are represented among the Precambrian latekinematic granites:

	CaO	Na_2O	K_2O	plag.	microcl.	quartz
NE of Ylivieska church, Finland (Wilkman, 1931)	0.74	4.40	4.57	39.85	29.19	30.90
W of Kamato, Sierra Leone (Wilson and Marmo, 1958)	0.6	3.63	5.04	30.7	29.4	30.5
Wankatana, Sierra Leone, (Wilson and Marmo, 1958)	1.1	3.90	5.10	32.7	29.8	31.1

In all the granites cited above, the potash feldspar is microcline and occurs side by side with albite or albitic oligoclase (An less than 15 %). The microcline is of high triclinicity (usually 0.9 or more), and short in sodium. According to Mäkinen (1913), microcline of the Tammela microcline granite (latekinematic) contains, however, 14.11 % K_2O and 1.80 % Na_2O. According to the x-ray determinations carried out by Dr. Julian R. Goldsmith of Chicago University (Marmo and Toini Mikkola, 1955) the microcline of the Sierra Leonean latekinematic granites is also highly triclinic (of almost maximum triclinicity) and very short in sodium. The same results were obtained from the x-ray examination of the microclines of Finnish latekinematic granites, carried out at the Geological Survey of Finland.

According to Tuttle and Bowen (1958), however, (*op. cit.*, pp. 99—100): »Crystallization of those two minerals (potash feldspar and plagioclase) side by side from a granite magma would require a temperature far below that at which this rock begins to melt in the laboratory with 4 000 bars water vapour pressure». Tuttle suggests that either such a rock is a metamorphic rock, or that a considerable amount of the plagioclase has unmixed from the potassium feldspar after crystallization. This was said by Tuttle and Bowen concerning the granite of western Rhode Island, an orthoclase granite, examined by Chayes (1952), who presented evidence to show that the mineralogical homogeneity of this granite demands a magmatic history.

This question is made still more difficult because the potash feldspar of the Precambrian latekinematic granites discussed here, is exclusively microcline of high triclinicity, and not orthoclase. This point, however, will be discussed later in this paper.

We still keep to the two possibilities proposed by Tuttle and Bowen: either the metamorphic or the present texture is the result of the unmixing of a single feldspar into potash feldspar and plagioclase.

If the granitic texture with a mosaic of separate grains of both feldspar is a product of metamorphic recrystallization, this possibly could also produce microcline from original ortoclase, and if this is the case, all Precambrian latekinematic granites would be metamorphic rocks. Is that possible? If this is so, non-recrystallized granites with a different texture should also occur, probably with single feldspar or with very strongly perthitic orthoclase. Such rocks, however, when they occur, are usually younger (rapakivi) than the latekinematic microcline granites or otherwise also texturally and compositionally different (see p. 52); or these rocks would have been rhyolites or something else of respective composition, which is, however, unknown among older rocks in such a magnitude of occurrence as would be expected if granites derived from such rocks.

Furthermore, there are certain known dykes, which have been taken as granite porphyries. Sometimes they are comparatively large. In Sierra Leone they occur in the central part of the Kangari schist belt and do not bear any connection to the latekinematic granites there.

In Finland, however, within the area around Lake Tarjanne and NE of it, there are veins and dykes from less than a meter to tens of meters in width, which, in the field, look like an aplite. Microscopy reveals, however, that the texture is not granitic, for the rock contains oligoclase and quartz insets in a fine-grained matrix consisting of microcline, plagioclase and quartz, micas being very sparse. Matisto (1961), described this rock as granite porphyry. Since then, the present writer has seen similar rocks around a large acid porphyrite body NE of Lake Tarjanne (Marmo, 1961 a). There they apparently grade into normal aplite with a mosaic of microcline, albite and quartz. The gradation takes place through aplite containing very resorbed remnants of oligoclase insets. This gradation is not, however, isochemical, but there is a marked difference between the composition of the granite porphyry and aplitic parts of the same dyke. The change of the chemical composition of the rocks mentioned is seen in the graph of Fig. 24. In granite porphyry the plagioclase is an acid oligoclase, but in the aplitic part of the same vein it is albite with An less than 10 %. This cannot be merely due to a decalcification, because simultaneously the ratio $Na_2O:K_2O$ is

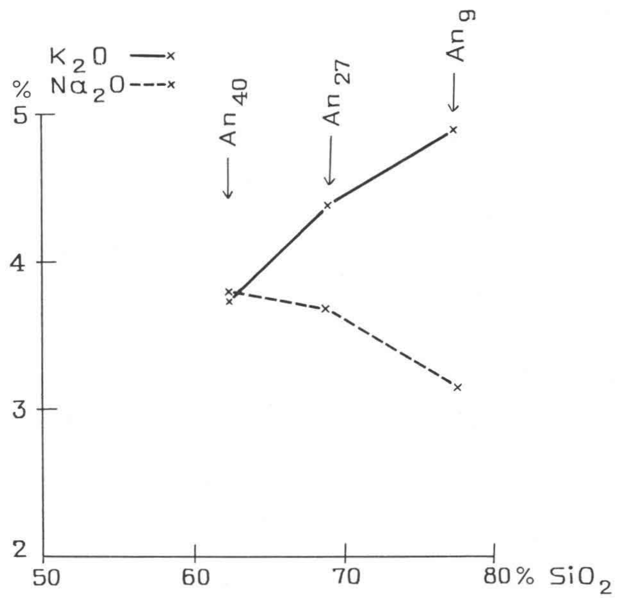


FIG. 24. Variation diagram for alkalies and silica of granite porphyries and granite aplite. For each sample analyzed, the calculated anorthite-content of plagioclase is indicated.

considerably higher in the granite porphyry than in the aplite. Thus the change of granite porphyry into aplite is parallel with the change of oligoclase into albite and the rapid increase in the content of potassium. The CaO-content is much more rapidly decreased (proportionally) than the content of sodium, and the decrease in the former is even quicker than the increase in the potassium content. Thus, from the analyses it may be deduced that the gradation from granite porphyry into aplite implies a considerable increase in the amounts of silica and potassium, the calcium content being thereby sharply decreased. The actual amount of sodium present need not be necessarily changed.

From this and other evidence (Marmo, 1961 a) it has been concluded that during the emplacement of the granitic material, there must have been different conditions of crystallization within the same vein or dyke, and that differentiation played an important role during the emplacement.

The evidence described above and the descriptions and observations of many petrologists from different Precambrian areas strongly support the view that the assemblage microcline — albite in a mosaic texture of granites cannot merely be the product of metamorphic recrystallization.

Another alternative set forth by Tuttle and Bowen (1958) is that of the possible complete exsolution of feldspars to such a stage that separate grains of comparatively pure microcline and albite result. This question has been thoroughly discussed by the author in his earlier paper (Marmo, 1958 a).

There seems to be a close connection between the modification of potash feldspar and the perthite in such a way that the series sanidine — sub-x-ray perthite — x-ray perthite — cryptoperthite — microperthite — perthite represents a decreasing temperature and an increasing time scale (Tuttle, 1952, p. 114). According to Laves (1952) the solvus temperature of any perthite is about the temperature of transformation from monoclinic to triclinic. In close agreement with the suggestion of Tuttle and Laves is the fact that in orthoclase granites (rapakivi *etc.*) the perthite is extremely common and occurs most usually as »hairperthite». In the syn- and latekinematic granites perthite, if present, is coarse and scanty.

According to Venkataraman (1962), and Venkataraman, Sharma and Xavier (1964) certain peralkaline granites of Rajahstan (Barmer District), which contain mesoperthitic soda-rich potash feldspar of variable symmetry and degree of perthitization, clearly indicate that both triclinization and exsolution are closely related phenomena, the perthite formation intensifying with the decreasing triclinization.

The cryptoperthites (Laves, 1952) are not two distinct phases but an assemblage of areas having a composition approaching values given by the appropriate exsolution curve. Thus they are solid solutions with compositional fluctuations much exceeding those of typical normal mixcrystals, and there are no distinct boundaries between the areas of different composition. Therefore it seems that below the solvus, the exsolution of albite through diffusion in solids proceeds to the point at which the sodium component incorporated into the »purified» potash feldspar corresponds to the Na-content of the potash feldspar at a given temperature. Such an exsolution would, under appropriate conditions, continue until a potash feldspar as pure and well ordered as possible is produced. Under less suitable conditions the exsolution would be arrested and remain unchanged through geologically long periods.

After complete exsolution, there should not be any need to force the exsolved albite out of the microcline crystal. Thus there is no reason why the process should continue beyond the stage of a coarse perthite and produce separate grains of albite and microcline.

Such a mosaic, however, would be easily produced, if the formation of feldspars were to take place at a sufficiently low temperature (at which only a little sodium can be incorporated into potash feldspar), and the accumulation of materials were sufficiently sluggish.

This reasoning may get some support from Barth's (1956) investigations concerning the method of determining the temperature of formation of the granitic rocks on the basis of feldspar-equilibrium. Using this method, Simonen (1961) has made an attempt to determine the temperatures of formation of some Finnish granitic rocks. He found that the composition of microcline extracted from a pegmatite granite corresponds to 580—630°C. For the same rocks, Mäkinen (1913) found, on the basis of the twinning of quartz, a temperature of 573°. For microcline granite (latekinematic), Simonen got 450°, which is exactly the same as that obtained by Barth for Norwegian »anatectic granite». For aplite, Simonen reports a formation temperature of 390°C. All these feldspars are microcline, the perthite being most common in pegmatites and rarest in aplite. It may also be mentioned here, that Guitard and Laffitte (1959) estimated 400—500°C as being the temperature of formation for the microcline granites of Costabonne, Pyrenees.

On the other hand, Simonen found a temperature of 730°C, for the postkinematic orthoclase granite, rapakivi, and there perthite is conspicuously abundant.

On the basis of the curves of equilibrium for feldspars and the observed composition of the feldspars of rapakivi Stewart (1959) has concluded that rocks with mantled ovoids have most probably been formed at a temperature of about 675° or 680°C.

Thus, these considerations also support the view that the latekinematic microcline granites and aplites have been formed at comparatively low temperatures.

Because, according to the discussion above, both metamorphic recrystallization and complete exsolution of feldspars seems unlikely, and, on the other hand, both mineral assemblage and formation temperature considerations support a non-magmatic origin for latekinematic microcline granites, some kind of origin other than magmatic should seriously be taken into consideration.

Microcline or orthoclase

A question of great importance is whether the cross-hatched microcline can be formed directly, or only through a stage of monoclinic form as Goldsmith and Laves (1954) claim on the basis of crystallographic considerations. This would mean that if microcline potash feldspar is cross-hatched, it must have been primarily a monoclinic orthoclase. In other words, probably most of the microcline in magmatic, migmatic and metamorphic rocks has previously been monoclinic potash feldspar. For a nontwinned microcline, on the other hand, they admit a primarily triclinic origin. From these conclusions one may continue and say that because a microcline is comparatively seldom completely unhatched, but mostly contains at least spots or edges with faintly developed and at first glance not discernible twinning, practically no primary microcline exists.

On the same basis, Guitard, Raguin and Sabatier (1960) likewise suggest that microcline of the granites and gneisses of the eastern Pyrenees has been primarily monoclinic. In the case examined by the authors cited, the distribution of monoclinic and triclinic potash feldspar is such that in katazone the monoclinic form is stable, but in meso- and epizones triclinization is characteristic, the microcline being predominant in mesozone.

The monoclinic ancestry of microcline, however, strongly contradicts the petrological observations made in the field on the synkinematic and latekinematic microcline, which is always perfectly well-hatched and of very good triclinicity.

Probably because Laves explained all the cross-hatched microcline as being secondary, MacKenzie and Smith (*e.g.*, 1959), in their answer to the paper of Ferguson, Traill and Taylor (1958), held that microcline was a result of the transformation of orthoclase, which, in their opinion, is the form potash feldspar takes at an elevated temperature, because heating experiments have indicated that at an elevated temperature the microcline will become disordered and finally be transformed into monoclinic sanidine. The heating experiments indicate definitely that this is the transition which takes place under elevated temperature (Goldsmith and Laves, 1954: under hydrothermal conditions at 525°C). They do not prove, however, that the vice versa-transition also takes place; and, as is known, microcline has never been synthetized by direct crystallization. Every attempt along these lines has yielded orthoclase at all temperature ranges used.

The only method known so far of artificially producing microcline is by the replacing of albite with potash feldspar, consequently »potassium metasomatically». Such syntheses were carried out first by Laves (1951), and later on by Wyart and Sabatier (1956) under hydrothermal conditions.

Thus we are not entitled to conclude on an experimental basis that orthoclase would go over into microcline at lower temperatures under all circumstances. We have definite proof that at low temperatures orthoclase can crystallize. In strictly determined conditions, however, microcline may likewise be formed. But there is no evidence to prove that if orthoclase is once formed it would, in a geological environment, necessarily be transformed into microcline were the temperature lowered.

In fact, there are very many observations from Nature which contradict such a possibility.

1. P o t a s h f e l d s p a r r e p l a c i n g p l a g i o c l a s e. This phenomenon is especially well known to students of many Precambrian synkinematic rocks, in which the plagioclase is partly or entirely replaced by potash feldspar which is then invariably microcline, perfectly well cross-twinned and of almost the highest triclinicity. The microscopy of such rocks shows all possible intermediate stages of such a replacement; and not infrequently, in such cases, at the ends of strongly saussuritized plagioclase crystals partly replaced by microcline, a fresh secondary albite may occur (Figs. 22 and 23). The present writer has never seen — either under the microscope or in literature — orthoclase replacing plagioclase in a similar way, and, furthermore, microcline is in such instances perfectly triclinic and excellently cross-hatched, and in all respects always similar, quite independently of the environment in which it occurs. The cross-twinning is well developed both in the sheared portions of the rock as well as in the perfectly homogeneous, massive and undisturbed parts. Thus the cross-hatching has developed together with the replacement, and the same applies to the triclinicity of potash feldspar. Therefore it seems very difficult to explain such a microcline as being formed primarily only as triclinic.

The artificial microclines produced by Laves and, later on, by Wyart and Sabaietr, illustrate just this case observed in nature, except cross-hatching which, in the natural rocks, seems to have developed simultaneously with the growth of the microcline crystal.

2. Homogeneous microcline granites. As has been seen in the description of the latekinematic granites, the orthoclase is absent there, and the microcline, as far as its triclinicity and twinning are concerned, is perfectly homogeneous and thoroughly cross-hatched.

Similar microcline occurs in the microcline aplites of all ages, starting from those bound to the latekinematic granites and continuing into those cutting the Alpine orthoclase granites.

3. Apophyses. Both in microcline and orthoclase granites minute veinlets and apophyses are common which, in the latter, as seen under the microscope, often penetrate the partly microclinized orthoclase grains. The potash feldspar of these apophyses, however, dissimilarly to the microclinized patches within orthoclase, is of high triclinicity and invariably consists of well and intensely cross-hatched grains.

In the orthoclase-bearing granites, the microcline is also always present, but only in subordinate amounts. Furthermore — as for instance in the rapakivi and Alpine granites — two generations of microcline are often seen: The older one is bound to the orthoclase and occurs in patches of inferior and very varying triclinicity and distinctive twinning; the younger one is represented by the above-mentioned apophyses and veinlets, in which microcline is homogeneously highly triclinic and well crosshatched.

Thus we may observe that there are rocks with homogeneously triclinic feldspar, or rocks with very non-homogeneous feldspar with all variations from monoclinic to microcline of inferior triclinicity, but there seems to be a gap between these two microclines. Potassic rocks with microcline of varying triclinicity would be expected to occur in much more abundance than they do, if all the microcline has derived from orthoclase, and especially so, because there are rocks containing younger but perfectly triclinic microcline and older potash feldspar, which is a mixture of orthoclase and poorly triclinic microcline. Such a situation is entirely inconsistent with the theory which claims monoclinic ancestry for all cross-hatched microclines.

Thus, one may epitomize that there are granitic rocks containing microcline which, as concluded on the petrological basis, have obviously grown as microcline; but there are also instances of microcline derived from orthoclase, in this case of very varying triclinicity. In certain syenites and monzonites, microcline is likewise non-homogeneous and intensely perthitic and orthoclase is absent. There the microcline may have derived from orthoclase, but it may also have grown directly as microcline of inferior triclinicity.

As mentioned, the direct synthesis of a microcline has never succeeded, but in every experiment orthoclase was formed. By a replacement of albite through potassium metasomatism under hydrothermal conditions, however, microcline has also been formed in the laboratory.

The heating experiments show that at elevated temperatures, microcline will be transformed into orthoclase. Orthoclase, on the contrary, under all the conditions experimentally available, remains monoclinic. Consequently, in the laboratory experiments, microcline is stable at low temperatures only, but orthoclase is formed and stable under all conditions. Thus, there must be additional factors acting to produce microcline naturally other than through a replacement of albite. One of the factors probably facilitates the Al-Si-ordering, which is typical of a triclinic lattice. It is possible, of course, that this factor is time. Because, however, there are several instances in Nature, which indicate that complete microclinization of an orthoclase with time has not taken place (for instance in the Precambrian rapakivi granites orthoclase is abundant, but still younger aplite cutting rapakivi contains perfectly triclinic microcline only,) it seems that the time factor is necessary rather during the crystallization of the feldspar than after it is completed.

The present writer has tried to explain this phenomenon (Marmo and Permingeat, 1957; Marmo 1958 b) as follows:

If there is some material to be crystallized as potash feldspar, and if the temperature is above that at which microcline still survives, an orthoclase will be produced under all circumstances. If the temperature is below that at which the Al-Si framework of microcline becomes disordered, there is the time factor to be considered as governing the modification of potash feldspar to be crystallized. If the introduction of material is comparatively rapid, there probably will not exist many possibilities for the growing Al-Si framework to be ordered, but an orthoclase still grows. If the growth is less rapid, some part of the growing crystals may already obtain some triclinicity (ordering), and then in »full-grown» crystal, »microclinized» patches may be seen, as often happens in rapakivi and Alpine granites.

The growth of the crystals being still more protracted, poorly ordered, usually intensely perthitic microcline (as in some syenites and monzonites) will be formed, and this will be the result also in such cases, where the growth is very sluggish but the temperature close to that causing disordering of potash feldspar.

If, on the other hand, the introduction of material yielding potash feldspar is slow and the temperature sufficiently low, there would be every possibility both for potassium and sodium to grow as separate and well ordered minerals. Thus microcline of good triclinicity and very short in sodium will be formed, and a texture with albite — microcline — quartz mosaic is then to be expected as the results of the crystallization.

It is to be pointed out, that the microcline does not grow, in a strict sence, directly as triclinic, but it may start its growth as monoclinic nuclei, which during the growth and due to the very long duration of the growth, are triclinized. In such a way and from the petrological point of view, the potash feldspar is growing as microcline. Therefore, this possibility does not basically contradict the statements of Laves, as claimed by Brown (1965).

The main conditions necessary for this formation of microcline are, consequently, slow crystallization under a sufficiently low temperature. These conditions were proposed by the present author already in 1955. In his recent work, Brown (1965) reached similar conclusions on a theoretical basis, but only regarding the triclinizition of monoclinic feldspar. To explain the presence of microcline porphyroblasts in metamorphic rocks, under considerably low temperature, he suggests (*op. cit.*, p. 345): »Thus the rate of growth of potassium feldspar porphyroblasts in metamorphic rocks, where such growth occurs below the temperature of stability of sanidine (orthoclase), which is around 500°C, must be rapid - - -. The subsequent stages of inversion twinning growth of twin domain and perthitic unmixing would proceed at very much lower rates». This requirement is not necessary, because a slow growth with contemporaneous inversion and perthitization is more logical, and in better agreement with the petrological findings and observations pointed out on the preceding pages.

But there is also another point of view to be considered, which is, however, insufficiently known so far: Baskin (1956) found that the twin pattern of authigenic triclinic potash feldspar is different from that of non-authigenic microclines. Therefore there may also be among the metamorphic microclines ideal or non-ideal microcline-type twinning (Laves and Soldatos, 1963), and this would explain many questions connected with the existence of the »pimary microclines» in granitic rocks.

Slow accumulation of potash feldspar, such as considered above, takes place during the replacement phenomena. This is obviously the case if granitization or feldspathization takes place, where the potash feldspar formed, in the instances mentioned, is always well cross-hatched and perfectly triclinic microcline. Orthoclase as produced by such phenomena has never been met with by the author.

The source of potassium

The question of the source of the potassium necessary for attaining granite composition, is likewise of the utmost importance to the granite problem.

At present, granodiorite and quartz diorite compose the majority of the synkinematic areas.

Furthermore, in many instances it is evident that the rock has been primarily a sediment, and especially so, if it grades into gneiss and mica schists. In addition to the examples mentioned on p. 14, we may also mention the apparently massive granodiorite of Orijärvi, Finland (Eskola, 1914), which according to the recent investigations of Tuominen (1957, 1961) contains magnetically discernible strips continuing from the surrounding gneisses through the granodiorite massif again into undoubtedly sedimentogeneous gneisses, thus indicating traces of continuous ancient strata.

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It has also been possible to demonstrate that if granodiorite derives from sediments, it is richer or as rich in sodium as are the sediments, but it contains distinctly less potassium.

Concerning the geochemistry of potassium in general, there seems to be a distinct tendency for this element to be enriched in the upper parts of the lithosphere. Hietanen—Makela (1953, p. 532) wrote that »there is a strong suggestion that granitic composition would represent a state of chemical equilibrium in the upper lithosphere. Thus the general tendency of all migrations of elements would be toward the formation of granitic rocks».

Also Eskola (1932) suggested that the granitic magma has a tendency to rise upwards. On the other hand, he also pointed out that the granitic rocks and not the basic ones, increase in amount with depth.

It has been shown from field observations that younger formations, such as the Tatra Mountains and the Alps, contain fewer granites than do the deeper sections, and the latter are especially abundant in the Precambrian areas. This, of course, may also depend upon the source of granitic material. If it derives from regionally metamorphosed sediments, then this behaviour of granites is consistent with the theory of their origin.

Tougarinov (personal communication) has pointed out that according to his lead-isotope studies, there is very strong support for the possibility that the oldest known rocks of true granite composition are younger than are the oldest known sedimentary rocks. Consequently, granite composition could not be attained before the sedimentation and sedimentary enrichment of potassium had sufficiently developed.

Still clearer is the tendency of potassium to be enriched in the upper parts of the lithosphere in the sedimentation processes, during which potassium is definitely enriched especially in clays. If then, under conditions of regional metamorphism, it would be released again, very large amounts of potassium are available. This source has also been considered by Eskola (1932). He points out (*op. cit.*, p. 460) that: »- - - contacts between basic rocks and granites showing cognate relations one to the other, reveal a picture of acid magma soaked out from crystalline rocks - - -». Furthermore he thought at that time, that the potassium released from sediments in this way, could cause both granitization and an accumulation of large granite masses which could intrude other rocks, and, in particular, they could occupy weak zones and axial culminations of folded areas, mainly occurring in such a way that »in the surrounding schistose rocks the folding axes in the nearest vicinity of granite masses are usually steeply inclined or nearly vertical». Regarding the intrusions themselves, Eskola was of the opinion that (*op. cit.*, p. 460) »The greater part of the masses moving by orogenesis are solid rather than liquid».

Wegmann (1930) compared the intrusions of latekinematic granites with salt domes, or diapires. Eskola also discussed the products, which would result after the expulsion of granite-forming materials from the sediments: the solid residue would be enriched in quartz, and thus form mica schists, for instance, even very pure quartzites could be formed.

Eskola still thought of a granite magma, which, in his opinion, is palingenic because there is no continuity from the normal differentiation series to his ideal granites, and (Eskola, 1956, p. 89) »- - - what indeed is a natural sequence of being palingenic, they are no end products of differentiation».

Palingenic or not

Even if it can be agreed upon that the potassium forming granites — usually richer in potassium than a eutectoid composition would require — derives from sediments (and from other pre-existing rocks), there is another puzzling question as to how the potassium would be released.

Eskola (1932, 1956), Simonen (1960) and many others who have studied granites, think that such a release of granitic material from the pre-existing rocks takes place palingenetically. If sediments are buried at sufficient depth, there should be a much elevated temperature, and this may cause a re-fusion of the rocks.

If we consider such an anatexis in dry conditions, there are many arguments against the possibility, and especially so, if the formation of granitic palingenetic magma is to be expected. In many cases the re-melting temperature would be very much higher than the original temperature of the crystallization of an igneous rock. Eskola (1932) takes quartz as an example, which may be crystallized from a hydrothermal solution, but, once is crystallized, it is a refractory mineral. The experiments of Kranck and McQuaig (1953) have also shown that the successive melting of natural rocks, under low water pressure and rapid heating, is such that the ferromagnesian minerals have started to melt earlier than the feldspar and quartz. Biotite and chlorite seemed to be the first minerals to melt.

The re-fusion takes place in an entirely different manner, if there is water present in sufficient quantity to establish hydrothermal conditions, and this seems to be the case in Nature where potash metasomatism is concerned, and a similar temperature range is obtained from the sodium-contents in microclines of granitic rocks (p. 60). Tuttle (1955), however, does not take this for granted, but says that the potash metasomatism has certainly taken place below the temperature of the granitic minimum, somewhere about 640°C. Furthermore, he estimated that with a geothermal gradient of 30°C per km partial melting of sediments might start to yield a biotite granitic magma with the above-mentioned temperature at a depth of 21 km. With a gradient of 40°C per km incipient melting could occur at a depth as shallow as 15 km.

Tuttle and Bowen (1958) observed, that in the granite compositions containing up to 10 per cent water, crystallization equilibria are nearly the same as in dry melts except that they go forward at much lower temperatures, and that about 6 per cent water is sufficient to nullify the incongruent melting of potash feldspar. The same partly applies also to an albite. At the greater depths (*op. cit.*, p. 49) »even a magma with a small initial percentage of water will eventually develop a residual liquid containing an appreciable amount of water. Thus a magma initially containing 1.2 per cent of water will have 12 per cent when the residual liquid is 10 per cent of the mass, unless notable amounts of water enter into hydrous minerals».

As a matter of fact, the presence of water in a granitic magma has been supposed very early in the history of geology. It was probably Spallanzani (1794) who already in 1792 noted the significance of the water present in magma. Seventy years later Scheerer (1862) applied this idea to granitic magma. Scrope (1825) who discussed the nature of primary magma and its differentiation, also paid attention to the water in it.

If we return to the sediments and other solid rocks which could re-fuse under conditions of regional metamorphism and orogenesis, water is present in quite considerable quantities especially in sediments. Therefore, under great pressure and temperatures corresponding to large depths a hydrothermal »anatexis» is theoretically possible. According to Winkler (1957), the graywackes, which form a large part of eugeosynclinal sediments, would yield true granite and then trondhjemitic magma by slight melting. He has shown that partial melting of the illitic type of clay has yielded exceptionally potassium-rich leucogranitic magma.

Kranck and Oja (1960) have carried out experiments with natural rocks to see if there is any possibility of an anatexis. The results are extremely interesting and promising. First of all, during the progressive heating (*op. cit.*, p. 22) »First signs of glass are always seen at the boundary between alkali-feldspars and quartz, and slightly later between plagioclase and quartz».

Still more interesting are their experiments on the sediments, which seem to be of especial importance as a source of potassium for true granites. In these experiments the graywacke started melting at a slightly higher temperature than the granites, but, as the authors suggested, the melting would probably have started at a lower temperature if a recrystallized sediment had been the object of experiments. Actually some of the textures obtained by Kranck and Oja in their partial melting experiments well cerrespond to those observed microscopically in the natural rocks, thus offering much support to the possibility of formation of mobile liquids carrying the easiest melting elements out from the original rock. Furthermore, the minerals first to melt and thus also first to move are feldspars and quartz yielding potassium and sodium, possibly as alumosilicates.

Wyart and Sabatier (1959) carried out re-melting experiments with the pelitic sediments under hydrothermal conditions, and the results obtained well support the possibilities outlined by the other fore-mentioned experiments along the same lines.

The temperature indicated by the mineral assemblages in the gneiss granitic and granodioritic part of the lithosphere are only seldom above 600°C, but usually they are considerably below this temperature. According to Ramberg (1952) such a situation (*op. cit.*, p. 1) »- - - may occasionally be explained by secondary recrystallization *in situ*, but in may cases one must assume that the rock matter was emplaced at submagmatic temperatures in the solid state».

He also pointed out, like many other petrographers of Precambrian, that (Ramberg, 1952, p. 224) »Quartz, acid plagioclase, and potash feldspar are undoubtedly the minerals which most commonly go together in forming conformable lenses, veinlets, and irregular clusters in gneisses and crystalline schists of different composition. In general, salic minerals appear to shun the chalcophilic minerals in metamorphic differentiation». And (*op. cit.*, p. 244) »The anatectic melt which starts to form under progressive metamorphism should, theoretically, have a eutectic granitic composition. Actually, the mobilized or introduced material is often monomineralic, for example, albite or microcline »augen» grow in gneisses, or quartz lenses develop in schists. And, also the core of most pegmatites, which should be the last part to consolidate on the liquidus theory, and hence should have a complex eutectic composition, is almost invariably monomineralic quartz».

It is, however, possible to object on well-established grounds to the last citation from Ramberg. In gneisses and granodiorites similar clusters and lenses, often occur of a non-monomineralic composition, and the conspicuously abundant aplite veins and dykes which are of granite composition are sometimes abundant, especially so if migmatites occur. On the other hand, in the latekinematic microcline granites gradually verging pegmatitic portions and quartz clusters are also common. It is revealed by the foregoing that a partial anatexis of the rocks — including sediments — is very much to be expected under conditions prevailing in the deep-seated portions of the earth's crust.

This remelting leads to the formation of interstitial »liquids», and because the sediments themselves contain large quantities of water, hydrothermal conditions prevail undoubtedly throughout the whole rock mass to be regionally metamorphosed and re-fused.

Additional data supporting the anatexis are available from the experiments carried out by Winkler (1958). He supposed that the clays may contain pore solutions of NaCl. Therefore he performed his experiments with clays under strong hydrothermal conditions in the presence of about 3 % to 4.8 % NaCl. At 670°C the melting of quartz and potash feldspars started, but at 675°C he had a melt with plagioclase, quartz and potash feldspar in the same proportions as they occur in true granite. This, of course, is an exceptional case, but it should be considered when discussing the possibilities of an anatexis in general.

As a matter of fact, starting from Sederholm's times, anatexis has been attributed to many granites around the globe and by various authors. Among the most recent writers giving credit to the anatexis Kizaki (1965) may be mentioned, who claimed anatectic origin for certain massive biotite granites of East Antarctica.

Hydrothermally expulsed elements

As opposed to anatexis there are also some other possibilities to be considered. If we start with clays, at the beginning of the consolidation and regional metamorphic recrystallization of the sediment, expulsion of all kinds of materials as watery solutions obviously takes place. At that stage probably hot waters would carry out alkalies (mainly potassium) and silica, possibly also alumina (as alumosilicates) from a sediment of clay-composition for example. Thus hydrothermal solutions already exist which may either move for considerable distances, or, to some extent, stay in the sediments, forming microcline veinlets or scattered grains in recrystallized sediments, which still invariably seem to keep considerable amounts of potassium in micas.

As an example of such a case, sulphide-graphite schists at Kaustinen, Finland, may be mentioned (Marmo, 1960 b). There schists have been interpreted as being formed from ancient sapropels. At Kaustinen, they cover a large lenticular area, which is cut and penetrated by several veins and dykes of pegmatites (quartz, feldspars and mica). These may also occur as lenses and clusters conformably within the sulphide-graphite schists. Because there are no distinct granites in the vicinity, a possible explanation for this is that the pegmatites have been derived from the sapropels due to the expulsion of alkalies and quartz by waters under hydrothermal conditions.

The sapropels themselves have thereby been impoverished in potassium and silica, but they still contain much potassium which, had palingenesis occurred, could easily have yielded granite composition. This is true not only for the original sapropels of pelitic rocks, but also for those of calcareous composition and for similar rocks in different localities in Finland:

	Sulphide-graphite schist of pelitic composition. Kittilä, Kiistala	Sulphide-graphite schist of calcareous composition. Nivala, Hitura
SiO_2	58.86 %	46.79 %
CaO	0.19	4.34
Na_2O	2.64	0.61
K_2O	4.37	3.38
Normative:		
albite	22.43 %	5.24
potash feldspar	25.75	20.02
anorthite	1.10	13.34
quartz	16.27	8.34

Peltola (1960) who investigated similar schists in the Outokumpu copper mine region, also found black schists short in potassium; on an average, however, analyses showed Na_2O 1.09 % to 1.97 % and K_2O 1.70 % to 3.14 %, respectively. The pegmatites are conspicuously less abundant there than they are at Kaustinen.

If the movement of expulsed, hot solutions continues through the stages of the regional metamorphism, the places of lowest free energy — cracks, fissures, fold openings — will be filled with such material crystallizing as aplites and pegmatites, as has obviously been the case in migmatized areas with a sharply verging aplitic network of metasome, »brecciating» or »interveining» the paleosome of various, mainly pelitic composition in large openings. This aplitic material may accumulate into clusters or larger bodies which often are texturally such, that in a homogeneous, looking aplitic mass there are limited areas of coarse, pegmatite-like portions, which grade without any distinct contacts into surrounding aplite, and this has a close association with the migmatite areas.

Experimental petrology has given much support to this possibility. According to Johannes and Winkler (1965), for instance, under a pressure of 2 000 bars, and at 600°C, quartz, K-feldspar and plagioclase will be dissolved by water. The solution always contains more silica than the minerals concerned if quartz is present. The dissolved components are transported within the temperature gradient in such a way, that Ca (derived from anorthite) and Mg (from biotite) together with silica are transported to *higher* temperatures, but Na, K, and Al together with the bulk of silica are transported to *lower* temperatures than the mentioned 600°C. The latter elements crystallize again from the solutions as quartz, K-feldspar, albite and muscovite. In the experiments lasting 10 weeks, a separation of Na and K is evident: albite is formed at temperatures from 420 to 470°C. K-feldspar (with some albite-component) is crystallized, together with quartz, at a wider temperature interval, but below 420°C. Thus the experiments not only support, but also clearly indicate that hydrothermal transportation and re-deposition of elements from the sediments necessary to form a granite, is entirely possible. Furthermore, the temperature intervals concerned, agree well with the supposed temperatures (as obtained from feldspar-composition) under which microcline-granites mostly have been crystallized (between 420° and 600°C).

Petrological classification of granites

The classification of granites based on their position in the kinematic evolution of orogenies, which has been chiefly used on the previous pages, is very satisfactory, but still has certain limitations which have bearings on the whole granite problem. The definitions syn-, late- and postkinematic are clear, but their interpretation in the field is too often an arbitrary one. Different geologists use different characteristics, in this connection, and especially where the latekinematic granites are concerned, there seem to be, in some cases, diverging opinions.

On the other hand, as could be learned from the foregoing pages, there are many petrological and petrographical characteristics, definitely different for different granites, which are easily ascertainable, and which cannot be omitted or neglected if an attempt is made to discuss the actual mode of the origin of granite.

Classification on a petrographic basis has also been used: biotite-granite, muscovite granite, two-mica granite, hornblende granite, *etc.* In these cases (for instance, Bodin, 1951, Arnould, 1961), the main reason for such a classification is to enable the distinguishing of synkinematic granites from each other and to establish some sequences for them. In detailed granite study, such a subclassification is, of course, both necessary and very useful.

As the description of granites in the foregoing has revealed, the main petrographic features are connected with differencies in the feldspars and their modifications. These characterics also reflect, to a certain extent and with known exceptions, the respective tectonic groups. This can be surmised as follows:

Synkinematic granites: K-feldspar is mainly microcline infilling interstices of replacing plagioclase, and usually being younger than the other constituents of the rock. It may also form porphyroblasts, which are mostly microcline, but sometimes also orthoclase or K-feldspar of inferior triclinicity. Plagioclase is usually oligoclase with An_{15-30}, more typically An_{25-28}.

Latekinematic granites: K-feldspar is predominantly well cross-hatched, highly triclinic microcline (orthoclase has so far only been met with exceptionally), and in most cases hardly younger than quartz and plagioclase. The latter is overwhelmingly albite or acid oligoclase with An_{2-15}, usually An_{5-10}.

Postkinematic granites: K-feldspar occurs at least as two generations. The older one is orthoclase of varying triclinicity, often with patches of microcline. The younger generation is represented by thin veinlets and interstitial infillings of well crosshatched, highly triclinic microcline. Plagioclase is mostly oligoclase (An_{20-30}), but may also be albite.

Furthermore, among the last-mentioned group of granites, K-feldspar is often extremely perthitic. The granites containing single feldspar (anorthoclase) and unusual accessory constituents may be distinguished as a special group.

It is still important to stress, that the feldspars cannot indicate the tectonic groups of granites, even though in most cases a correlation between them is observable. If the K-feldspars are concerned, the potash feldspar of synkinematic granites is certainly metasomatically introduced excepting the case of porphyroblasts. The microcline of latekinematic granites is formed at somewhat lower temperatures (p. 64), 350° — 500°C, but the orthoclase and microcline of inferior triclinicity (predominantly of postkinematic granites) must have been formed at somewhat elevated temperatures. The temperature of formation of single feldspar is highest, and the granites containing it may be very close to magmatic conditions or even represent such conditions. Thus, if genetical questions of the granites are to be discussed, there may be more use in a petrological rather than a tectonic classification of granites.

A classification on a petrological basis may be done in several ways. In certain cases it may be very useful to classify the rocks into, *e.g.*, muscovite-, biotite-, two-mica-, hornblende-, epidote-granites. In some other cases such a classification may be even misleading. In the following the purpose of a classification is to facilitate the understanding of the genetical problems of granites. Therefore it is based on the character of feldspars. On the other hand, such a classification must be a flexible one which can be enlarged using additional indications of other constituents, if necessary.

1. *K-Na-feldspar granites* containing predominantly only one feldspar, which is mostly highly perthitic (*e.g.* »Younger granites» of Nigeria).

2. *Orthoclase granites* which mainly contain orthoclase and oligoclase. Microcline is present as patches or young veinlets (*e.g.* rapakivi and most Alpine granites). K-feldspar is strongly perthitic.

3. *Microcline-oligoclase granites*, in which microcline is mostly perthitic and of varying triclinicity. This type is not very common, but is also met with among latekinematic granites.

4. *Porphyroblastic orthoclase-microcline granites* in which porphyroblasts are of varying symmetry (triclinicity 0—0.8). Potash feldspar of the ground mass is mostly microcline of high triclinicity (*e.g.* some porphyroblastic granites of Central Finland).

5. *Porphyroblastic or even-grained microcline-oligoclase granites* (*e.g.* most synkinematic granites).

6. *Microcline-albite granites* which are mostly aplitic. Potash feldspar generally non-perthitic (*e.g.* most latekinematic granites of Finland).

These are the groups. In addition, especially for microcline-albite granites, epidote is sometimes characteristic (*e.g.* unakites and helsinkities), the presence of which may then be indicated by calling the rock microcline-albite-epidote granite. Similarly the presence of riebeckite or columbite or hornblende may be shown in the rock name.

Black (1965) has reached very interesting conclusions in connection with his investigations on the younger granites of Nigeria and Niger. For the latter he found that the granites have been formed along two different trend lines: 1) granites poor in alumina which have aegirine-amphibole granite as a final product; 2) granites rich in alumina represented by biotite granite at the final stage. In Nigeria and Niger, such a classification is of petrological importance, and similar trends have also been locally observed within the same granite mass, in Finland (Otanmäki), but of a very local importance only. This example may indicate, that in certain localized cases, various petrological classifications may be adopted, which could also have general bearings.

It is important to stress once more, that this classification does not cancel out the tectonic classification, but it should be used either together with the latter, or in such cases where the tectonic or kinematic groups cannot be determined with sufficient reliability.

ON THE ORIGIN OF GRANITES

There is no doubt that locally granite magma really exists in such a way that it can be proved by direct observation. That is the lava approaching granite composition, which may sometimes grade into a fine-grained granite (Erdmannsdörffer,

1950) or the cases when the granite porphyry and quartz porphyry veins clearly indicate the existence of a magma of granite composition (Mehnert, 1959). The Nigerian younger granites of Jos Plateau most probably belong to the same category.

Hjelmqvist (1961) described from Sweden an area with intrusive diabases, quartz monzonite, granophyric granite and quartz porphyry, the two latter grading into each other. There he claims, on a good basis, the magmatic origin for the granite composition.

The theory claiming igneous formation for granites, mainly worked out by Bowen (1928), has received much support from later experimental work he has conducted in association with Tuttle, notably in systems involving high water pressure, which is the essential factor in geological processes especially where regional metamorphic or related conditions are concerned. The system $NaAlSi_3O_8$ — $KAlSi_3O_8$ — SiO_2 — H_2O gives us an answer to many questions about granite petrology. It shows that the crystallization of melts in this system tends to produce mineral assemblages approaching granites with increasing water-vapour pressure. First quartz and single K-Na-feldspar will crystallize simultaneously; at higher water concentrations K- and Na-feldspars crystallize separately, and, if some Ca is present, this happens even at lower water concentrations. Thus granite can crystallize directly from a melt, providing water is present. On the other hand, these findings can also be transferred to anatectic melts.

If in the pre-existing rocks the materials to form a granite composition are available, a granite melt can be formed at a temperature less than 700°C and water pressure of some 2 000 kg/cm^{-2}. The Alpine granites may belong to such granites, and especially certain riebeckite-granites (see p. 53) containing soda-rich alkali-feldspar. Increasing water concentration will facilitate remelting and the melting may be partial or complete.

There are, however, real granites with typical texture and composition, which do not fall into this category. In them the most characteristic constituent of the granites, potash feldspar, is definitely younger than the other constituents, and obviously metasomatically formed (pp. 22 and 62). The synkinematic rocks of granite composition (p. 21) belong to this category.

True granite composition with equigranular texture and equal age of the main conctituents of the rock, is represented by late- and postkinematic granites, which involve the actual problem of the origin of granite. These granites are widespread and especially typical of the Precambrian areas (p. 36).

At present, it may be considered as a commonly accepted opinion, that granite is closely associated, both in time and space, with mountain building, with the geosynclinal belts, with thick beds of sedimentary and volcanic rocks, and with the regional metamorphism within them. In many places metamorphic rocks of obvious sedimentary origin pass gradationally through granodiorites into granite. There is also evidence, that potassium — the crucial element for the formation of granite — moves upwards during geological processes, and that its enrichment into the upper-most parts of the Earth's crust is especially advanced in the sedimentation cycle. In other words: There seems to be connection between originally sedimentary environment and the occurrence of granites. Furthermore, according to Tougarinov (oral communication and his presentation at the colloquium of absolute ages in Nancy, 1965) there are also observations, that according to the isotope determinations, the oldest sofar investigated true granites (that is the potash-rich rocks of granite composition) are less than $2\,800 \times 10^6$ yrs old. Consequently they are younger than the known oldest sorted sediments. After these remarks we may proceed with the origin of the late- and postkinematic granites.

The present author has adopted the following theory to explain the origin and emplacement of such granites. There may be truly magmatic granites, which derive from juvenile sources. The majority of granites, however, have their potassium and other constituents mainly from sediments, and more or less in the following way: The formation of sediments definitely favours the enrichment of potassium. In actual fact, among the residual sediments, the clay composition is close to that of a granite (Table I, Anal. 1), except that it is often poorer in quartz. By a direct recrystallization of clays, in theory, a granite could already result.

Field observations point out, however, that such an origin of granite is not common, because recrystallization of such sediments usually yields a quartz diorite or granodiorite composition, which means that if a clay is converted into regional metamorphically recrystallized rock, this change is obviously accompanied both by impoverishment in potassium and enrichment in sodium, the latter possibly being a consequence of the former. Thus the regional metamorphism may cause an expulsion of potassium and water from the pre-existing sediments. This will result in the establishment of hydrothermal conditions and therefore in a transport of practically all materials necessary for the formation of a granite composition. If the regional metamorphism is tectonically simple, granodioritization (p. 24) of sediments with local granitization phenomena will probably result. If, on the other hand, the regional metamorphism is accompanied by strong tectonic processes the places of lower free energy will certainly attract the hydrothermally removed materials, and they will be accumulated there forming aplitic, pegmatitic or granitic veins, dykes or larger bodies, often appearing as the metasome of migmatites. This may explain to a large extent the formation of microcline granites.

But another kind of granite formation will certainly develop as well. Many observations indicate that palingenesis is not an infrequent phenomenon in the deep-seated rocks, including sediments. Also there (p. 67) partial re-melting may produce granite composition, which would lead to the formation of granites very similar to those considered in the foregoing. The orthoclase granites, in particular, must have been generated in this way (p. 52). As an example, the Herefoss granite of Norway will be taken, which according to Elders (1963) has been emplaced as a diapir. According to him, the contact relations and the internal structure of the granite, all indicate that the major part of the granite went through a mobile phase. Thus (*op.*

cit. p. 48) »- - - the Herefoss granite is an anatectic body, formed in the later stages of the same cycle of metamorphism which produced the non-magmatic granites of the region. - - - Locally the granitized material, being less dense, was able to migrate 'en masse' down the P.T. gradient and intrude older strata». The chief objection to his interpretation is that the feldspar appears to have formed at about 500°C. In the opinion of the present writer, there is not necessarily any controversy, because both the palingenesis and emplacement must have taken place under hydrothermal conditions. Under such circumstances the temperature of 500°C is high enough to make the body behave in an apparently magmatic manner during its emplacement. Because in such granites potash feldspar (microcline) and acid feldspar have often crystallized simultaneously and side by side — thus also contradicting magmatic origin — the accumulation of the material has been comparatively slow to enable the joint crystallization of potash feldspar and acid plagioclase. According to Tuttle and Bowen (1958), under sufficient water pressure, the anatectic melting may also proceed until a melt, with about 6 per cent water, is formed. Under these conditions, one per cent of the water in a rock could melt 16 per cent of the rock, provided the rock contains granitic material. To explain the emplacement and formation of both microcline and orthoclase granites under hydrothermal conditions and slow crystallization, the following possibility will be set forth:

— If the accumulation of crystallizing granitic material is not very protracted, and the temperature is simultaneously somewhat elevated, the potash feldspar will crystallize predominantly as orthoclase which is also conspicuously perthitic, because under such conditions the exsolution of the sodic component is contemporaneous with crystallization yielding sodium-bearing orthoclase and very finely dispersed stringers, lamellae and spots of albite within the crystal.

— If the temperature is below that at which microcline is transformed into orthoclase, and also the crystallization is sufficiently sluggish to permit the ordering of the Al-Si framework into triclinic, triclinic spots will appear within the orthoclase crystals. This seems to be most common among the orthoclase granites such as the rapakivi and post-kinematic Alpine granites.

— With a further lowering of the crystallization rate, at a temperature similar to that mentioned above, the strongly perthitic microcline of inferior triclinicity will be produced, as exemplified by many syenitic and monzonitic rocks with such potash feldspar.

— If the growth of crystals (= introduction and accumulation of material to be crystallized) is very sluggish, under low temperature and hydrothermal conditions, well ordered microcline and separate grains of acid plagioclase will result. Examples: the majority of the latekinematic microcline granites, aplite cutting postkinematic orthoclase granites, microcline produced by granitization of synkinematic rocks or occuring as a replacement for plagioclase.

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