GEOLOGINEN TUTKIMUSLAITOS

BULLETIN
DE LA
COMMISSION GÉOLOGIQUE
DE FINLANDE

N:o 201

ON GRANITES

BY
VLADI MARMO

WITH 21 FIGURES AND ONE TABLE IN TEXT

HELSINKI 1962

GEOLOGINEN TUTKIMUSLAITOS
BULLETIN DE LA COMMISSION GÉOLOGIQUE DE FINLANDE N:o 201

ON GRANITES

BY
VLADI MARMO

WITH 21 FIGURES AND ONE TABLE IN TEXT

HELSINKI
1962

Helsinki 1962. Valtioneuvoston kirjapaino

CONTENTS

ABSTRACT

The paper is a review of the granite problem. New materials from Finland and Sierra Leone are described. Taking into account also the results of experimental petrology and mineralogy, conclusions are reached favouring a metasomatic origin for microcline granites rather than an origin from a melt. For orthoclase granites and such microcline granites that contain strongly perthitic microcline a crystallization from a melt seems to be possible.

INTRODUCTION

According to the definition given by Johannsen (1941, p. 124), the granite is »characterized by quartz forming more than 5 and less than 50 per cent of the quarfeloids, and by a 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 is close to those accepted by many other authors for a granite. In common use, however, the word granite has often designated 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 right, because thereby among the »granites» rocks are often included those 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.

The 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, whichever 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 fullfilling the above-mentioned requirement are inserted in this triangle, there appears a very distinct maximum at about one-third albite + one-third orthoclase + one-third quartz.

Within the same range, but still distinctly deviating from the last-mentioned maxim, fall the »ideal granite» of Eskola (1950), as well.

When considering the world-wide literature on granites, it can be noted, that the majority of papers discussing granites and their origin are, in actual fact, not concerned at all with granites! 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 there 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 actual granites as defined above.

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 there often occasional and restricted to tectonized places, or occurring as veins, indisputably younger than is 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 fullfilling the compositional requirements set forth above for a granite, may still vary very much and in several respects. 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., are to be considered as well.

In a 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, the microcline being by far the most predominant form of potash feldspar present. Schermerhorn (1960, 1961) took a type of Skye granite as unusual, yet this is common among the Alpine granites. Also the pure microcline-albite granites, which are very wide-spread among the late-kinematic 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 the orthoclase is uncommon, but with an important exception presented by rapakivi they contain 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 the observations made from microcline granites. Another large group of geologists pay attention chiefly to younger granites with very perthitic feldspar, mostly orthoclase, from which group are taken almost all the examples discussed, for instance, in the paper by Tuttle and Bowen (1958). The present author has stressed the importance of distinguishing microcline and orthoclase granite groups and discussing them separately (Marmo, 1958 a), and I am still convinced that this is the way to approach the problems of granite origin and emplacement.

TECTONIC GROUPS OF GRANITES

The differentiation of granites into different groups is actually as old as the study of granites, because no student of these wide-spread 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. In 1932, 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 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 palingenetic.» 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. In this group belong the older Archaean granites of Fennoscandia, which include many primary gneisses, and hardly any non-orientated rocks at all. Eskola 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) instrusions, and are well 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 further later in this paper (p. 15).

LATEKINEMATIC GRANITES

Latekinematic granites are those, the magmatectonic behaviour of which 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». Very recently, 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 (1948 a).

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 yet 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 CLASSIFICATIONS

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 classing the granites of the map area on the arbitrary petrological or relative age basis. Therefore he developed his tectonic groups: 1) synorogenic, and 2) late-orogenic. The characteristics of both mentioned 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 late-orogenic 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 of the composition from a granite to peridotite, the acid members forming, however, the large majority, and *(op. cit.*, p. 284*)*: »Die Gesteine gehen oft allmählich in einander über und bilden hiernach zu schliessen eine schöne Differentiationsserie.» This statement is entirely at variance with Eskola's definition for his latekinematic granites, as well as with all the later definitions of resp. granite, considered in the present paper.

Saksela assumed, that his synorogenic granites have been intruded due to tangential movements resembling those of Alpine overthrusts. The late-orogenic 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 syntektonic 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, Wahl (1936 a, 1936 b) made likewise 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 1936 b, 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 intra-orogenic». 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 the time when the magmatic way of thinking was much 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 up to the present day and in most countries.

Yet, whatever the theories that exist to explain the origin of different granites, there are two or three definitely distinguishable groups of granites, which most likely are to be explained on a tectonic basis.

In the following, the present writer will express his personal opinion concerning the classification of granites, and this will be done also considering both the compositional and mineralogical differencies 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, actual granite composition occurring there as patches or stripes, 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 the 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 not the purpose to describe here some synkinematic areas in detail. Some general features, however, are necessary here to give a basis for discussion of the granite portions of the synkinematic rocks.

Synkinematic »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, the contacts may be seen as 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 striking inhomogeneity of the mass, which may appear as 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 any homogeneous mass at all, but that the rocks there referred to comprehensively as granite are in fact, to a large extent, tonalites, admellites 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 of 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, or also in West-Africa, including the observations of the present writer in Sierra Leone. Furthermore, if large coherent areas occur, they are mainly quartz- or granodiorites or porphyroblastic granites. The last-mentioned rocks may deserve here some more detailed description and discussion, but before that some other common features of synkinematic areas should be considered.

This may also be 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 of Precambrian to Early Cretaceous ages, are in part discordant and in part concordant, and those of the catazone predominantly concordant.

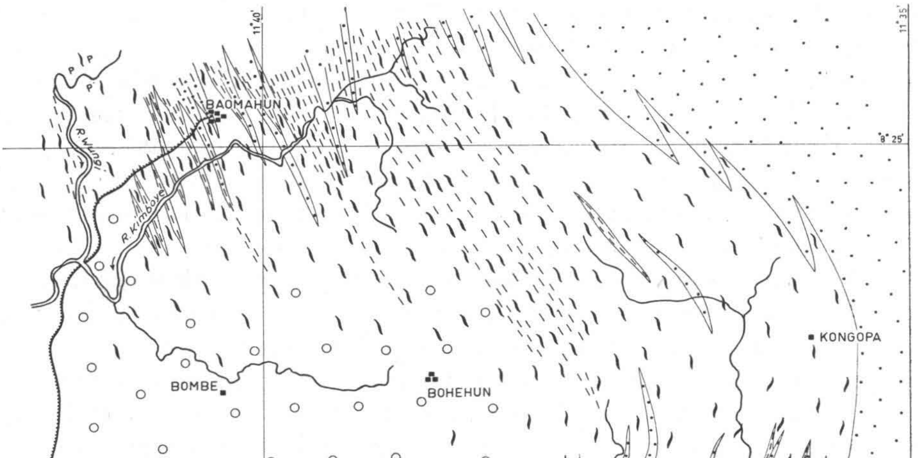

Fig. 1. Geological map of the southern end of the Kangari Hills, Sierra Leone. 1 = amphibolite; 2 = garnet-cummingtonite schists; 3 = diabase; 4 = hornblende gneiss; 5 = gneissose schists; 6 = gneissose granodiorite; 7 = porphyroblastic granodiorite; 8 = pegmatite.

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

In Central Sierra Leone, to the south of the Kangari Hills (Marmo, 1962) there is a large area composed of apparently homogeneous, gneissose synkinematic »granites» (Fig. 1). In detail, however, a more careful 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. In length, this zone, which is also richer in quartz than the gneisses of the environment, extends for several miles, weakening southwards and sidewise, 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 afore-mentioned quartzites. Therefore it is very striking to find magnetite-rich strips also in the synkinematic gneisses, always associated with the afore-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 there forming 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, for instance, the occasional occurrences of large inclusions of amphibolite in the gneiss are often mantled by a zone — from a few decimeters to tens of meters in width — containing hornblende.

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. In such a way, 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 south 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 titanium-contents of magnetites extracted from different rock types of the schist belt and embracing salic rocks has been determined (Marmo, 1959). Thereby it was found that among the synkinematic rocks there are those with TiO_2 less than 0.3 % 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, even then 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.

In actual fact, this is displayed by the distribution of some minor constituents in synkinematic and latekinematic granodiorites and granites, as such. So, for instance, for the granitic rocks of Osnizk, Russia, Matkovskij (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 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 there, and that actually magmatic material is hardly more abundant than are the sedimentary and volcanic materials. According to Matkovskij (1956), for instance, zircon of such rocks is mostly of relictic character.

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 gradually over into gneissose rocks often showing sedimentary relic texture. Some of these bodies are even-grained and quartz dioritic in com-

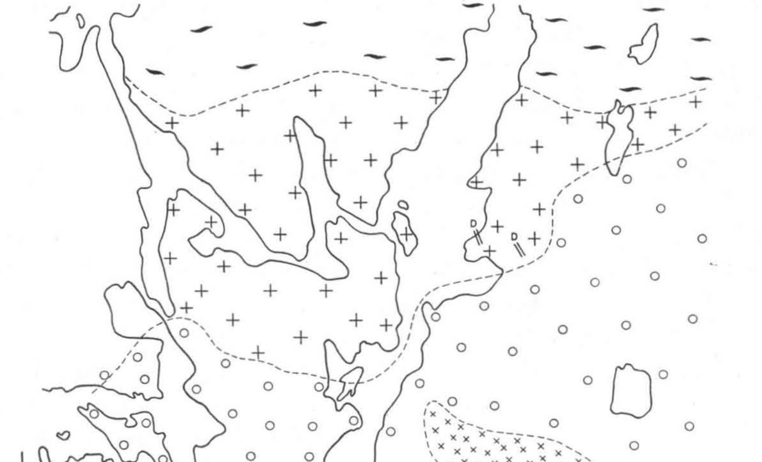

Fig. 2. Geological map of the area around Keuruu, Finland.

position, 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 palingenetic 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 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 differentiation 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. This 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 palingenetic 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 writer, that keeping in mind the thickness of the earth crust as well as the information about it so far available, the palingenetic origin would attract here somewhat more than the juvenile one.

In his recent paper, Simonen (1960) seems to pay very much attention to the 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 statement 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 from this paper of his. 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 occurrence 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, and 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 of synkinematic areas everywhere, forming often comparatively homogeneous bodies. In West

Africa 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.

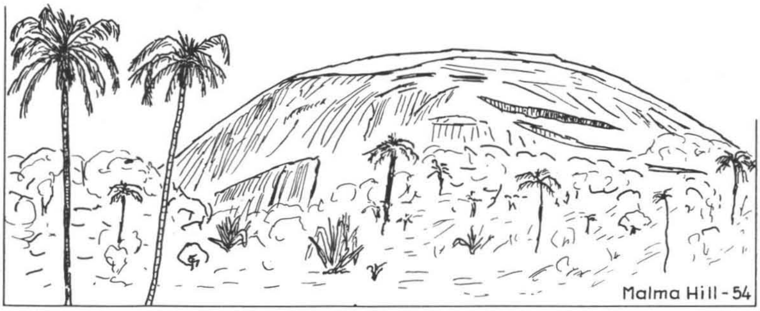

Fig. 3. Tor-like hill composed of porphyroblastic granodiorite. Sierra Leone.

The names porphyroblastic granite and granodiorite are here used for the rocks of mainly granitic bulk composition containing large, usually pink insets of feldspars and white ones of oligoclase or quartz in a matrix most 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 porphyroblasts and not phenocrysts.

The geology of such areas occupied by porphyroblastic granites is very similar in the different areas 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, 1956 b). There the hills themselves, 4 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 quartz, 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. Here may be mentioned 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. In Central Finland, around Äänekoski, the situation is exactly similar, but the dimensions are larger, and so on.

The origin of such porphyroblastic granites has been thoroughly discussed by the present writer (Marmo, 1956 b), where it was 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 heat of the material, been concretionary concentrated into porphyroblasts. This would explain why the matrix of these rocks is homogeneously quartz- or granodioritic, and why the porphyroblasts frequently grow across the fractures (Fig. 4) and also occur in undisturbed form in the surrounding gneisses, as well as 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 and the joint action of pressure and of a local increase in the temperature there, where the doming began. This also may explain why in the most recent investigations carried out by A. Matisto (oral communication), orthoclase has sometimes been found in similarly shaped rocks of the Tampere area in Finland. On the other hand, this explanation makes it questionable whether the emplacement of such granites took place at the synkinematic or at some later stage of the orogenic evolution.

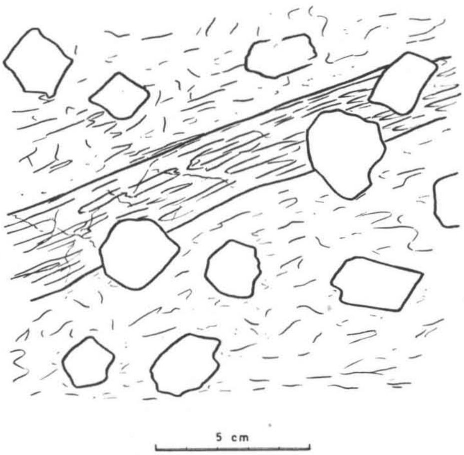

Fig. 4. Porphyroblasts of microcline growing across a fracture. Gbengbe Hills, Sierra Leone.

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 carried out by him 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 feldspars by K-rich feldspars in tbe cooler rock and *vice versa*. This mechanism of alkali metasomatism has been demonstrated on a small scale in the laboratory.

SYNKINEMATIC GRANITES

Among the synkinematic rocks, as mentioned above (p. 13) the portions of true granite composition are underordinated in amount, or they may even be occasional. From what is 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 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 there appears a discontinuity — gap — 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. 18. Raguin (1957) in the second

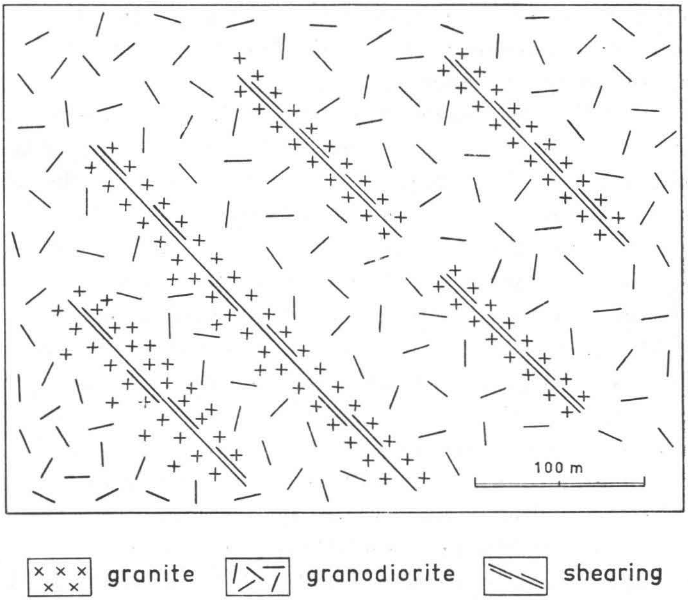

Fig. 5. The granitic portions follow the sheared lines in a granodiorite mass. N of the Sula Mountains, Sierra Leone.

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. 5 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 everywhere younger than any other constituents of the rock, and that it occurs mainly as infilling of fissures or in the interstices of other constituents. 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.

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 there, 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 that time, Simonen obviously thought that granitic material invaded from the outside, which caused the granitization of granodiorite. As will be shown below (p. 26), the present writer would explain similar phenomena in such a way that the »granitizing» potassium derives from the granodioritic material itself.

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

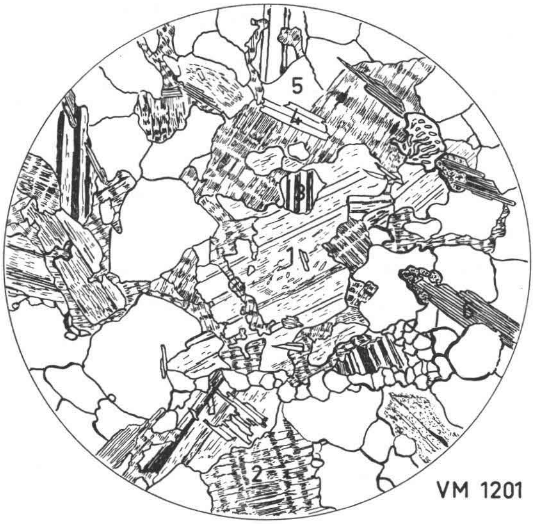

Fig. 6. Microcline occurring in a synkinematic granite as the youngest constituent of the rock. Sierra Leone. 1 = plagioclase; 2 = microcline; 3 = younger, albitic plagioclase; 4 = muscovite; 5 =quartz; 6 = biotite. Magn. 40 x.

Fig. 6 illustrates very well how the microcline occurs usually in the synkinematic rocks, clearly indicating that this mineral is younger than the other constituents of resp. 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, in the mesozone the granitization has played a role of subordinate significance only, 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): »Hypotheses, 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.»

GRANODIORITIZATION OR GRANITIZATION

It has been mentioned above (p. 15) that through the synkinematic granodiorites, the continuation of sediments occurring within the schist belt

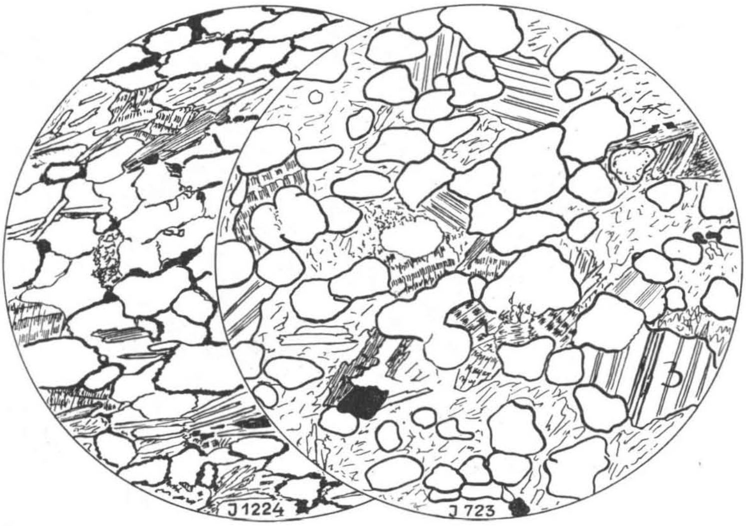

Fig. 7. Interstitial microcline in a slightly granitized magnetite-cummingtonite quartzite (J 1224) and in a gneiss rich in quartz (J723). Kangari Hills, Sierra Leone. 1 = microcline; 2 = biotite; 3 = plagioclase; white is quartz; solid black is magnetite. Magn. 40 x.

of the Kangari Hills, Sierra Leone, can easily be traced. 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. 7 illustrates two examples of rocks from the quartzites going over into granodiorite: The left 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 well rounded »clastic» grains of quartz in abundance.

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

Fig. 8. Garnet-bearing amphibolite from a well preserved strip within granodiorite. Amphibole mostly biotitized. Sierra Leone. Magn. 40 x.

the expense of the quartzite, are always aplitic, and chiefly consist of quartz, oligoclase and microcline, the latter being the youngest constituent.

The tendency of the synkinematic granitic-looking rocks to attain the 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 Centarl Finland often contain only very minute grains of microcline or none at all (Fig. 8). 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 the 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 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 by 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 for 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) uniformly 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 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 at many places in Central Finland) seem in general to have originated from clay and sand sediments, which all contain considerable amounts of potassium, as well. 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 lessen the ratio of K_2O to Na_2O as much as it 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 writer 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 explains also 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. 70).

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 as to that of potassium in places corresponding to the lower free energy. Numerous examples of this kind are available in regional meta-

Fig. 9. A portion from an intensely minor-folded veined gneiss. Vuolinko, Eastern Finland. 1 = plagioclase-rich pegmatite; 2 = folded mica schist.

morphic 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, often intensely folded (Fig. 9). 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.

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 non-orogenic 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 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 to granitization the main role in the formation of granitic rocks, and 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 the only potash feldspar of the synkinematic granites of the area under discussion, together with the experimental findings of Goldsmith and Laves (see p. 60) 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 ± 25° C as a 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° to 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 already may be attained at 4 to 6 km.

The granitization process may take place anywhere in the earth's crust, where a sufficient temperature prevails, and the necessary materials for granitization are available. From field evidence it seems (p. 24) 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, granodioritic 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 by 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 again 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 big 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.

Due to similar accumulations of heat, re-fusion of the rocks may take place as well.

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. 18), 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 possible converting of hornblende into biotite and 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 it fills the cracks and fissures, or it 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 complicated impregnation of microcline. With further replacement the microcline impregnations are united into a few larger, irregular crystals, finally forming one single crystal, which contains remainders 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 the different views as to the origin of the potassium which causes 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 that the granitizing material is derived from a granitic melt, and in such a 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, still admitting that the introduction of alkalies may also take place as silicates (Goldschmidt, 1920), which would probably be the case if the potassium derives from sediments (Marmo, 1958a). 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, there very seldom can be seen a replacement of Mg- and Fe-bearing minerals, 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 signs 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 writer differs here from that of Härme mainly in that instead of a granite melt as the source of the granitizing potassium, it is assumed here that the potassium derives, under hydrothermal conditions, from the sediments, and elsewhere it may cause granitization. In some cases, if examined locally only, both explanations may appear as correct. In Fig. 10, 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. The former, if we take it that the aplite is the source of granitization, would indicate that the diffuse contacts are a result of 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 was 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 of the aplite vein, resulting in aplite similar to that in Fig. 11. Furthermore, the microcline veinlets and grains around the veinlet with diffuse contacts are typical of much too broad zones on both sides of the veinlet for them to be explained reliably as caused by the aplite. In Fig. 11, 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

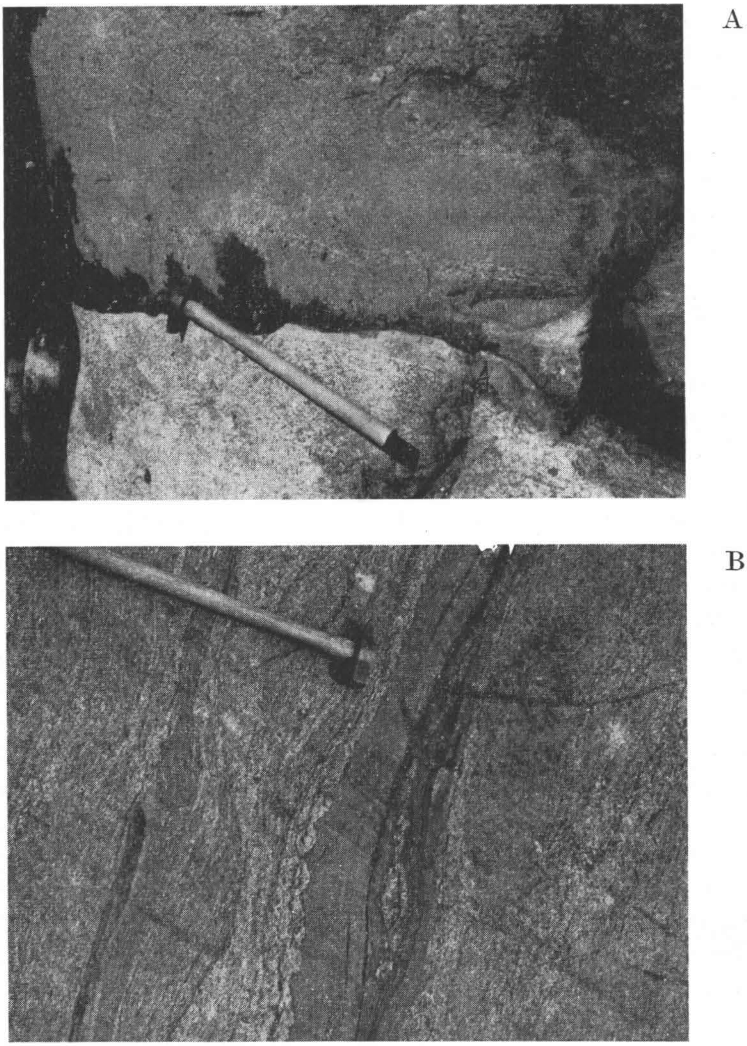

Fig. 10. Portions from a migmatite. A: Diffuse margins between aplitic vein and surrounding gneissic portion; B: Sharp contacts between amphibolitic strip and enclosing microcline-rich gneiss. Otaniemi, near Helsinki, Finland. Photo E. Halme.

detect that such patches are usually restricted also with the depth, and their shape may be irregular or that of a lense.

The distribution of additional potash feldspar occurs either as porphyroblasts or also 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.

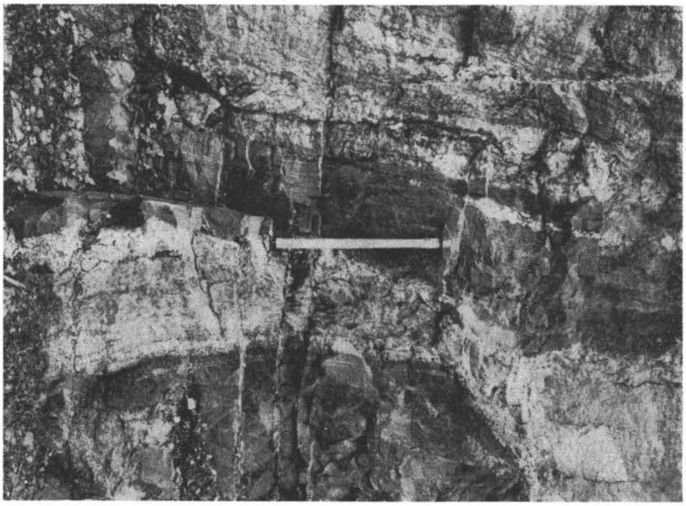

Fig. 11. Dark amphibolitic »interbeds» in a migmatite. The upper light portions are composed of »gneissose aplite», the gneissosity being there relic structure of very intensely granitized schist. The light portion below the hammer is more homogeneous aplite. Otaniemi, near Helsinki, Finland. Photo E. Halme.

The potash feldspar may thereby be formed in another way, as well: It may derive from other potassic minerals, which under metamorphic conditions become decomposed. Nykänen (1961) has described gneisses containing microcline from western Finland, 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 opened cracks and fissures, it may there form — being transported as silicates and aluminates — aplites, and the granitic material, under hydrothermal conditions, may then be transported even long distances and thereby fill up fissures and veins of all possible sizes.

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 many 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) into 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. 8), 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 Archaean and subsequent time, he considers as a late term 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.»

The duality of granites was, however, resolutely rejected by the recent representatives of the French school, Perrin and Robault, who expressed their 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

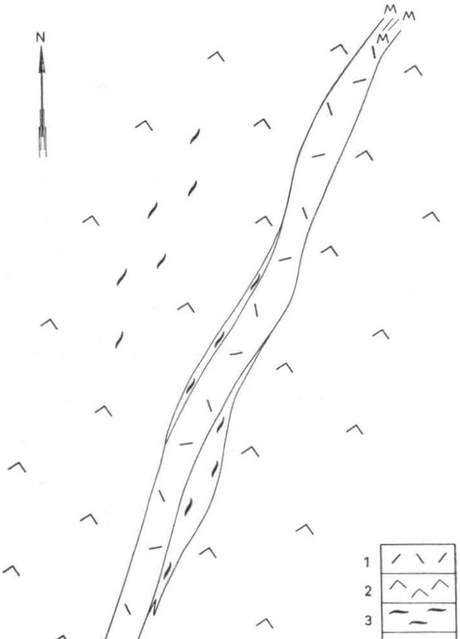

Fig. 12. A large dyke of latekinematic granite cutting through synkinematic granodiorite. E of Sula Mts., Sierra Leone. 1 = granite; 2 = granodiorite; 3 = gneiss; 4 = migmatite.

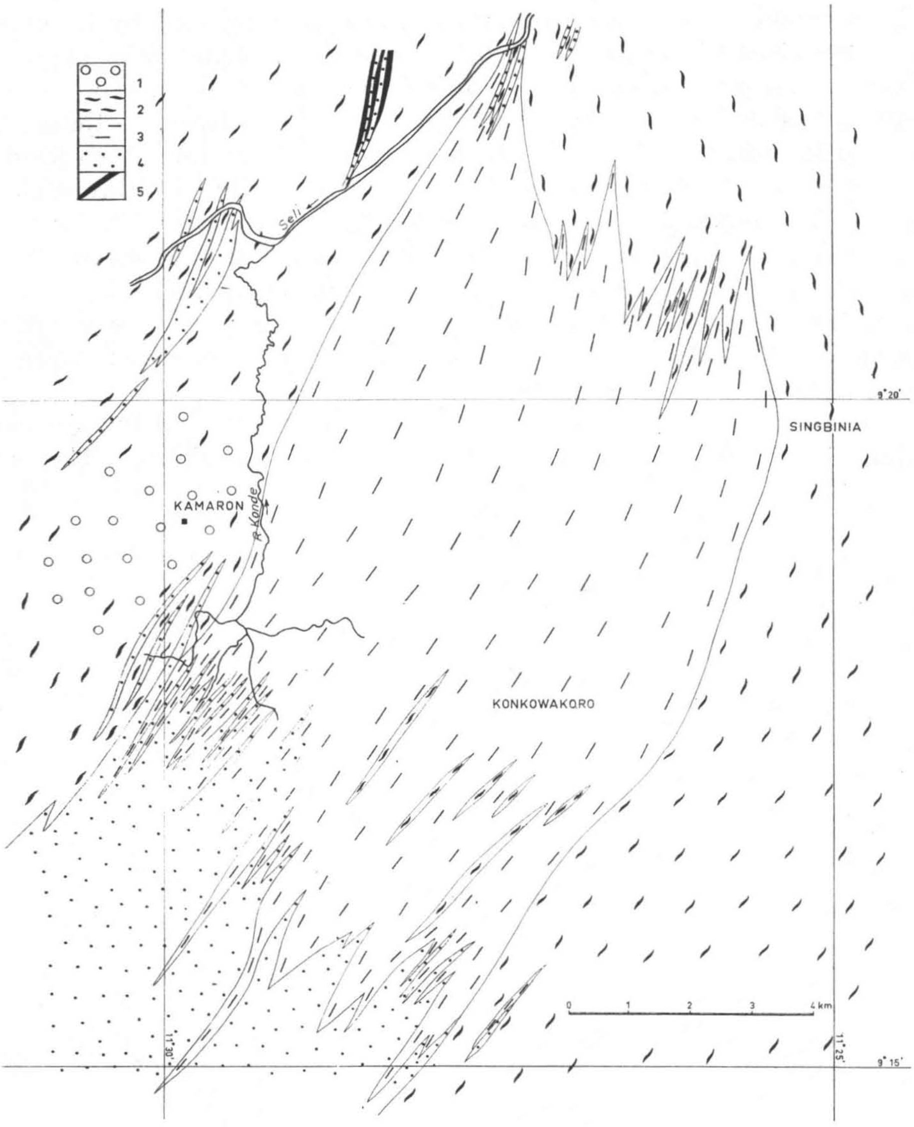

Fig. 13. Latekinematic granite at the northern end of the Sula Mts., Sierra Leone. 1 = porphyroblastic granodiorite; 2 = gneissose granodiorite; 3 = pink, latekinematic granite; 4 = amphibolite; 5 = magnetite-cummingtonite quartzite.

form bosses and stocks of considerable size, or also dykes varying from several kilometers to a few meters in width, or also as minute veinlets like those typical of migmatites. None of these occurrences possesses chilled margins, the presence of which would indicate an intrusion of hot material

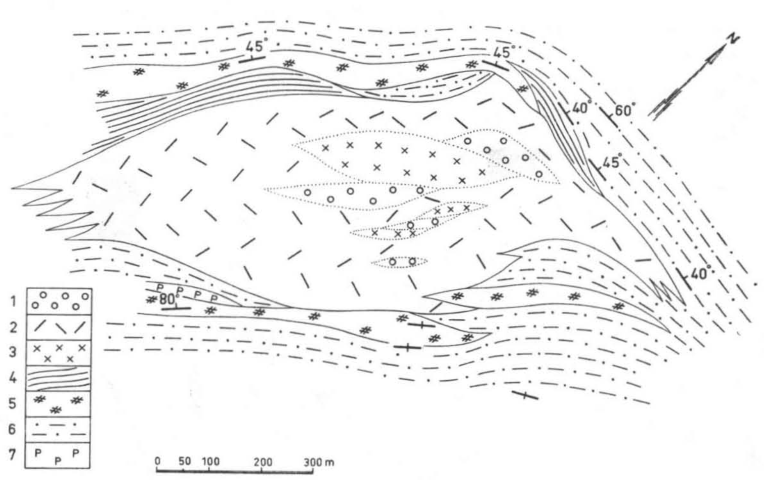

Fig. 14. Molybdenite-bearing latekinematic granite in the crest of a gentle fold. Wankatane River, Sierra Leone. 1 = porphyroblastic granodiorite; 2 = latekinematic aplitic granite; 3 = latekinematic granite containing MoS_2; 4 = fine-grained gneiss; 5 = amphibolite; 6 = schist rich in talc and serpentine; 7 = pegmatite.

Fig. 15. Distribution of latekinematic granites (solid black) in southern Finland, according to Simonen (1960, p. 65).

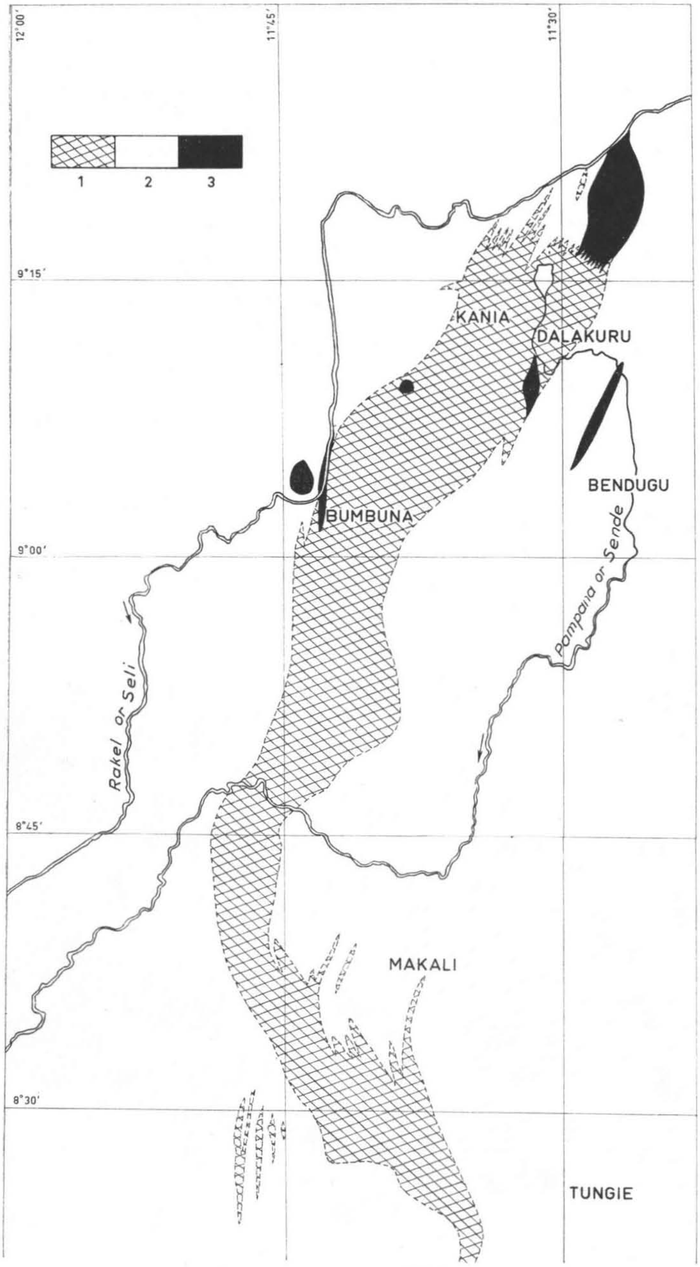

Fig. 16. Distribution of latekinematic granites in Central Sierra Leone. 1 = schist belt of the Sula Mts. and Kangari Hills; 2 = synkinematic rocks embracing the schist belt; 3 = latekinematic granite.

into a cold environment. In Figs. 12 to 14 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 well as the migmatites made up of older rocks and latekinematic granite. In Fig. 15 the distribution of the latekinematic granites in southern Finland, according to Simonen (1960), is illustrated. They are far more sparse in Central Finland, and in Central Sierra Leone they are almost rare (Fig. 16).

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 there 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 gorphyroblastic granodiorite, grading and finally fading out into the nonpranitized rock.

A similar dyke of the same size has been examined by the present author in Central Sierra Leone (Fig. 12), there cutting gneiss and granodiorite, and forming migmatites, as well as granitizing gneiss at the ends of the large granite dyke.

In Fig. 13 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 upon gneisses in the east, and upon 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 the geological maps, such a situation strongly supports an emplacement of the pink aplitic body from below through the strata and causing slight uplift of embracing rocks, resulting in an interfingering with the broken layering of strata at the ends of the body.

In Fig. 14, a molybdenite-bearing latekinematic, pink, aplitic granite is emplaced in a bent of strata caused by a gentle fold. Also there the side contacts are sharp, but at the ends migmatization of the schists as well as short distance granitization together with locally observable interfingering occur.

All bodies mentioned above may contain skialithic remnants, which are conspicuous, too, in the molybdenite-bearing granite body of Fig. 14.

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. 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 much fine needles of sillimanite (Kulonpalo and Marmo, 1955). Furthermore, according to Härme (1960), the southern Finnish granites may also be rather coarse, and sometimes pegmatite-like with skialithic inclusions in varying abundance. 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 do not appear to be any distinct age differences between different feldspars, rather the microcline and plagioclase seem to have been formed contemporaneously. 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. Values of 0.8, however, have been observed in an aplitic granite, possibly derived from rhyolitic material, in Central Finland (Marmo, 1961 a). Guitard and Laffitte (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.

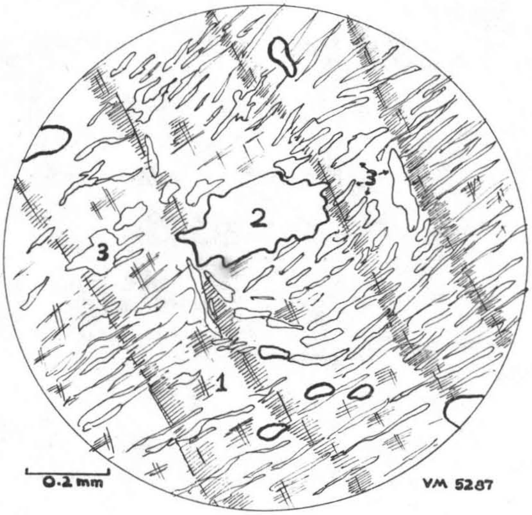

Fig. 17. Microcline crystal in a hornblende-bearing granite. Between Mano and Kenyema, Sierra Leone. 1 = microcline; 2 = quartz; 3 = plagioclase.

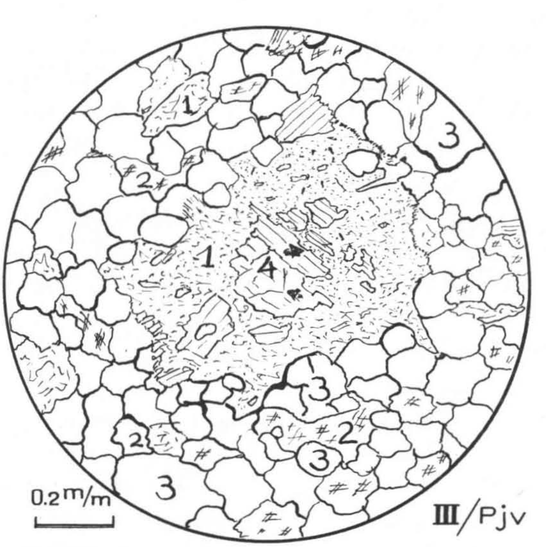

Fig. 18. Sericitic plagioclase inset in granite porphyry. Pihlajavesi, Finland. 1 = sericitic plagioclase; 2 = microcline; 3 = quartz; 4 = muscovite.

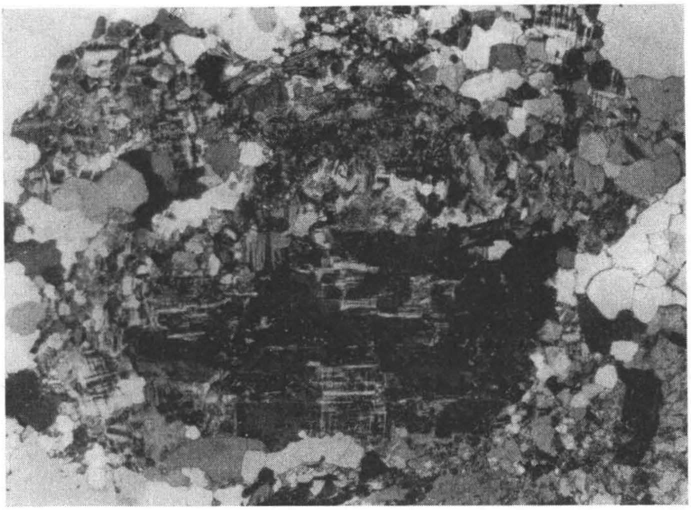

Fig. 19. Microcline replacing sericitic plagioclase in granodiorite. Pihlajavesi, Finland. N +, magn. 25 x.

Another conspicuous feature of the microclines of the latekinematic granites is that they contain sodium in very small amounts only, 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 there 14.54 % K_2O—1.26 % Na_2O and 14.11 % K_2O—1.80 % Na_2O respectively.

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, 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. 17), oligoclase and hornblende. But, as mentioned, this is not in any way typical for actual latekinematic granites, in general, and, if in the last-mentioned rocks perthite occurs, it is a microperthite and not the »hairperthite», which is the common form in the first-mentioned 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 there is seldom mention of the presence or absence of perthite. Therefore available examples are not very plentiful. The Sierra Leonean latekinematic granites do not usually contain but traces of perthite. In Finland, concerning the microcline granites of the Tampere area, Seitsaari (1951) remarks that the distinctly crosshatched 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. Aimo 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, Erkki Mikkola (1941) did not mention perthite. According to Simonen (oral communication) the presence of perthite in the Finnish latekinematic granites is not a conspicuous feature. Of a great number of thin sections of latekinematic granites from within the area of Pihlajavesi, Central Finland, about two thirds contained weakly developed perthite, but one third did not contain any at all.

PLAGIOCLASE

In the latekinematic granites, plagioclase tends to be albitic, as described by many students of 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 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_{11} to An_{15}, in a few cases with less than An_{11}.

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}. 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 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 usually well separated crystals besides the similarly occurring microcline, and in most of the cases examined both feldspars seem to be of the same age, as is not the case in synkinematic granites, where microcline is always and distinctly younger than plagioclase.

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 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 only to a certain extent a true microcline granite for there are also areas occupied by an epidote-albite rich rock, which could rather 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 much as 10 % in volume. But still: despite the Ca-content of epidote, if from the bulk composition of an epidote-bearing granite the normative plagioclase is calculated, 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 % of modal epidote, the An-content of normative plagioclase remains as low as 2.2 % only, and this 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 % of epidote, and only 0.19 to 1.90 % K_2O, the plagioclase being albite. Such rocks Ramberg (1952) considers to be the best representatives of the amphibolite-epidote facies within the gneiss-granite rocks.

But still closer are the Sierra Leonean rocks, richest in epidote, 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	1.95	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-contents of the former rocks.

The relationship between the ordinary microcline granites, and the epidote-rich varieties 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, such an explanation cannot be accepted without important reservations. These epidote-albite rocks are more like those described by Kranck (1931), occurring 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.

First of all: 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 there 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 are low: on the 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 the thin sections.

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

$$\underset{\text{anorthite}}{4CaAl_2Si_2O_8} + \underset{\text{orthoclase}}{KAlSi_3O_8} + \underset{\text{water}}{H_2O} \rightarrow \underset{\text{zoisite}}{2Ca_2Al_3Si_3O_{12}OH} + \underset{\text{muscovite}}{KAl_3Si_3O_{10}OH} + \underset{\text{quartz}}{2SiO_2} \tag{1}$$

Fig. 20. Microcline replacing plagioclase in a synkinematic granite. At the upper end of the latter is younger and perfectly fresh albite. South of the Kangari Hills, Sierra Leone. Magn. 40 x.

or by the introduction of lime:

$$3CaAl_2Si_2O_8 + Ca(OH)_2 \rightarrow 2Ca_2Al_3Si_3O_{12}OH \tag{2}$$

$$\underset{\text{anorthite}}{} \qquad \underset{\text{lime}}{} \qquad \underset{\text{zoisite}}{}$$

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 and at the expense of anorthite, which adequately explains the fact that the plagioclase in these granites is usually albitic, or nearly so. Fig. 18 illustrates a granite porphyry showing strong saussuritization of the plagioclase insets, often resulting in real pseudomorphs after plagioclase, composed of fine, compact grains of epidote. Analogous features are often observed in the latekinematic epidote granite as well, 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. There epidote and hornblende occur in close association and, in addition, sphene, usually not very common in the latekinematic granites, occurs, but also small rounded grains of apatite — all in close association with each other. 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:

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

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

The equation is, however, somewhat approximate one only, because the Ti of hornblende also uses some lime and silica for 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

$$(4) \quad 2\ \underbrace{2CaO \cdot 3\,(Mg, Fe)\,O \cdot 2\,Al_2O_3 \cdot 6SiO_2 \cdot H_2O}_{\text{hornblende}} + \underbrace{H_2O}_{\text{water}} \rightarrow$$

$$\underbrace{4CaO \cdot 3\,Al_2O_3 \cdot 6SiO_2 \cdot H_2O}_{\text{zoisite}} + \underbrace{6MgO \cdot Al_2O_3 \cdot 3SiO_2 \cdot 2H_2O}_{\text{aluminous serpentine}} + \underbrace{3SiO_2}_{\text{quartz}}$$

As 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.

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

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.

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

The present author would add that, in addition, 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

Among the postkinematic granites, as defined on p. 9, both microcline and orthoclase granites occur, although the latter are very unusual, and may be even 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 strongly perthitic orthoclase in abundance, this form of potash feldspar being preponderant over microcline in these rocks, and Eskola held that this granite is 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 strikingly 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, in 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 characteristic of a rapakivi: The potash feldspar of the rapakivi granites is predominantly orthoclase, entirely absent or very 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 of the Urals. Also the rapakivi of Brazil (Goñi, 1961) contains orthoclase which, as well as microcline, is usually enveloped in an oligoclase 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, such microcline, which is usually younger than orthoclase, always occurs, but in subordinate amounts, and forming interstitial or fissure infilling. This microcline is mostly of high triclinicity. Stewart (1959), however, has described the rapakivi of Penobscot Bay, Maine, which, according to him, 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 %.

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, and also Sato (1961) probably did not think of the kind of potash feldspar when he supported the views of Backlund on a petrochemical basis. Also Goñi (1961) gave his support to a similar explanation for the origin of rapakivi.

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 on the Andes, and they have been found in the Central Urals, as well. 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 is there 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 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, as well. Marmo and Permingeat (1957) have described in detail this sort of veins from Azegour, Morocco. There such veins vary considerably in width, ranging from a few millimeters to several meters. As mentioned, they are pure microcline granites which cut the orthoclase granites with sharp contacts.

THE GRANITE PROBLEM

GENERAL

As is shown in the description of the synkinematic rocks, the quartz diorite there predominates over the granodiorite, and the granite composition is comparatively seldom to be found. Furthermore, it has also revealed that the potash feldspar, which is almost invariably well cross-hatched microcline of high triclinicity, is younger there than the other constituents of the rock, occurring in interstices or as fissure infilling (Fig. 6). Thus it seems that the potash feldspar there, 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 difficult 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 feldspars and micas also 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 for the granites of the Ukraine (Polevaja, 1956):

	bulk sample	mica	potash feldspar
Plagioclase granite, Saksagan ...	$2\,000 \times 10^6$	$1\,970 \times 10^6$	$2\,050 \times 10^6$
Granite, Kirovograd	$1\,760 \times 10^6$	$1\,800 \times 10^6$	$1\,790 \times 10^6$
Rapakivi, Korsun	$1\,640 \times 10^6$	$1\,590 \times 10^6$	$1\,500 \times 10^6$

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

rapakivi, bulk sample	$1\,440 \times 10^6$
orthoclase ovoids of rapakivi	$1\,420, 1\,400, 1\,360 \times 10^6$
graphic feldspar of rapakivi pegmatite	$1\,400 \times 10^6$
mica of rapakivi pegmatite	$1\,500 \times 10^6$

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

These observations on the K/A ages well support the views based on the petrologically observed relative ages of potash feldspars 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 writer, to deal with the actual granite problem itself one need only consider the late- and postkinematic granites, which have a texture not uncommon within 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 feldspars and micas extracted from different granitic rocks have 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, and very presumably at the latekinematic stage of the orogenic evolution there.

Once more it should also be pointed out that, in the Precambrian areas, within a single area a 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. 44, however, a »series» within the latekinematic granites themselves may still sometimes occur, but then there is a sequence, sometimes occurring 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 rather homogeneous mass.

THE ASSEMBLY POTASH FELDSPAR WITH ALBITE

As mentioned above (p. 41—43), 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 the 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 3.45 %, 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 18 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 is cutting 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 there 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 the 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, as established by the experimental investigation. But 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-vapor 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, which is an orthoclase granite, examined by Chayes (1952) who also 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 here discussed, is exclusively microcline of high triclinicity, and not orthoclase. This point, however, will be discussed later in this paper.

We still stick to the two possibilities proposed by Tuttle and Bowen: either 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 feldspars is the product of metamorphic recrystallization, then this possibly could also produce microcline from original orthoclase, 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 these rocks would have been rhyolites or something else of respective composition, which is, however, unknown in older rocks in such a magnitude of occurrence as is to be expected if granites derive 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 with latekinematic granites there.

In Finland, however, within the area around Tarjanne Lake 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 .The microscopy revealed, however, that the texture is not that of granite, for the rock contains oligoclase and quartz insets in a fine-grained matrix consisting of microcline, plagioclase and quartz, micas being very sparse there. 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 the Tarjanne Lake (Marmo, 1961 a). There they apparently grade into normal aplite with a mosaic of microcline, albite and quartz. The gradation takes place through aplite con-

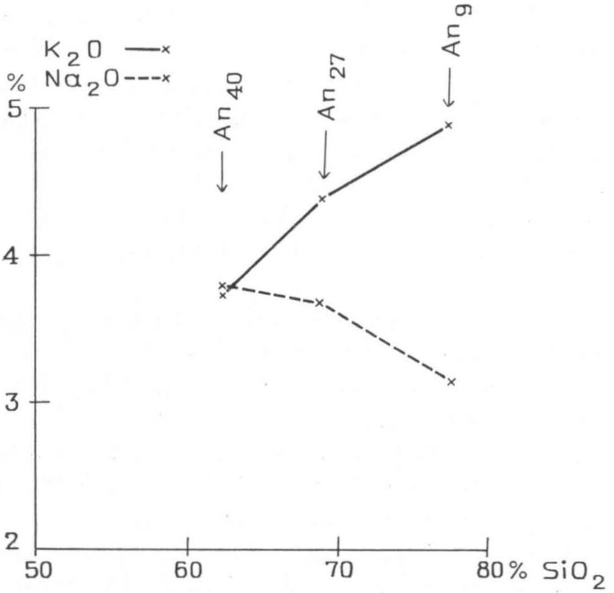

Fig. 21. Variation diagram for alkalies and silica of granite porphyries and granite aplite. For each sample analyzed, the calculated anorthite-content of plagioclase is indicated.

taining very resorbed remnants of oligoclase insets. This gradation is not, however, isochemical, but there is a marked difference in the composition of the granite porphyry and aplitic parts of the same dyke. The change of chemistry of the rocks mentioned is seen from the graph of Fig. 21. 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 a decalcification, because simultaneously the ratio Na_2O: K_2O is considerably higher in the granite porphyry than it is in the aplite. Thus the change of granite porphyry into aplite is parallel with the change of oligoclase into albite, and a rapid increase of the content in potassium; and the CaO-content is much more rapidly decreased (proportionally) than the content in sodium; also the decrease of the former is even quicker than the increase of the potassium content. Thus, from the analyses it may be deduced that the gradation from granite porphyry into aplite implies considerable increase of the amounts of silica and potassium, the calcium content being thereby sharply decreased. The actual amount of sodium present need not be thereby 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 this 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 be the product merely 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 eralier 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 »hair-perthite». In the syn- and latekinematic granites perthite, if it is present, is coarse and scanty.

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

After complete exsolution, there should not be any need to force the exsolved albite out from the microcline crystal. Thus there is no reason why the exsolution 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 takes place at a sufficiently low temperature (at which only a little sodium can be incorporated into potash feldspar), and the accumulation of materials is sufficiently sluggish.

This way of thinking 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 commonest in pegmatites and rarest in aplite. It may also be mentioned here, that Guitard and Laffitte (1959) estimated for the microcline granites of Costabonne, Pyrenees, 400—500° C as being the temperature of formation.

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

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

Thus also these considerations 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 not to be likely, and, on the other hand, both mineral assemblage and formation temperature considerations support a non-magmatic origin for latekinematic microcline granites, as described above, some other kind of origin than magmatic should be seriously 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 claim on the basis of crystallographic considerations. This would mean that as soon as microcline potash feldspar is cross-hatched, it must be primarily a monoclinic orthoclase. In other words, probably most of the microcline in magmatic, migmatic and metamorphic rocks have previously been monoclinic potash feldspar. For a non-twinned microcline, on the other hand, they well 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 for katazone the monoclinic form is stable, but in meso- and epizones the triclinization is characteristic, the microcline being predominant in mesozone.

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

Probably because Laves explained all the cross-hatched microcline as being secondary, MacKenzie and Smith (e. g., 1959), too, 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. All attempts along these lines have yielded at all temperature ranges used orthoclase.

The only method known sofar of artificially producing microcline is by a replacement of albite by potash feldspar, consequently »potassium metasomatically». Such syntheses have been 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 if the temperature is lowered.

In fact, there are very many observations from nature which contradict such a possibility:

1. Potash feldspar replacing plagioclase. 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 very fresh secondary albite may occur (Fig. 20). The present writer has never seen — either under the microscope or in the literature — orthoclase replacing plagioclase in a similar way, and, furthermore, the microcline is in such instances perfectly triclinic and excellently cross-hatched, and in all respects it is similar, quite independently of the environment in which it occurs. The crosstwinning is well developed both in the sheared portions of the rock as well as in the perfectly homogeneous, massive and undisturbed parts. Thus there 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 only primarily as triclinic.

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

2. Homogeneous microcline granites. As has been seen from the description of the latekinematic granites, there the orthoclase is absent, and the microcline, so 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 it invariably consists of well and intensely cross-hatched grains.

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

Thus we may observe that there are rocks with homogeneously triclinic feldspar, or then 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, has obviously grown as microcline; but there are also instances of microcline derived from orthoclase, then 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 derive 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. This factor probably facilitates the Al-Si-ordering, which is typical of triclinic lattice. It is possible, of course, that time is such a factor. 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 very sluggish 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 crytallization.

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

THE SOURCE OF POTASSIUM

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

In recent days, 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 most 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 the traces of continuous ancient strata.

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 it is so for the granitic rocks which increase in amount with the depth, and not the basic ones.

It is shown from field observations that younger formations, like the Tatra Mountains, Alps, etc., contain many 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.

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, reveals a picture of acid magma soaked out from crystalline rocks — — —». Furthermore he thought at that time that the potassium released in this way from sediments, could cause both granitization and also an accumulation of large granite masses which could intrude other rocks, and, in particular, they would 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 from mica schists, for instance, even the very pure quartzites could be formed.

Eskola still thinks of a granite magma, which, in his opinion, because there is no continuity from normal differentiation series to his ideal granites, is palingenic 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: How would the potassium 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 in sufficient depth, there should be 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 this 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 as an example quartz, which may be crystallized from a hydrothermal solution, but, once it is crystallized, 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 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 found from the sodium-contents in microclines of granitic rocks (p. 58). Tuttle (1955), however, does not take this for granted, but says that the potash metasomatism has taken place certainly 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 abovementioned 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 to an albite, too. 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.»

If we return to the sediments and other solid rocks which could re-fuse under conditions of regional metamorphism and an orogenesis, there, especially in sediments, water is present in quite considerable quantities. 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 by melting a little true granite and then trondhjemitic magma. Partial melting of illitic type of clay has been shown by him to yield an 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 alkalifeldspars and quartz, and slightly later between plagioclase and quartz.»

Still more interesting are their experiments on the sediments, which seems to be of especial importance as the 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 correspond 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, there the minerals first to melt and thus also first to move are feldspars and quartz — as elements: 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 afore-mentioned experiments along the same lines.

The temperatures 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 many 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 *(op. cit.*, 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 calcophenic 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.»

To the last citation from Ramberg, it is, however, possible to object and on well established ground: Similar clusters and lenses, in gneisses and granodiorites, often occur of a non-monomineralic composition, and the conspicuously abundant aplite veins and dykes which are of granite composition are sometimes abundant there, and especially so if migmatites occur. On the other hand, in the latekinematic microcline granites gradually verging pegmatitic portions and quartz clusters are common, as well. 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 results in the formation of interstitial »liquids», and because sediments themselves contain large quantities of water there, undoubtedly, hydrothermal conditions prevail 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 in general the possibilities of an anatexis.

HYDROTHERMALLY EXPULSED ELEMENTS

As opposed to the anatexis there are some other possibilities to be considered, as well. If we start with clays, at the beginning of the consolidation and regional metamorphic recrystallization of the sediment expulsion of all kind of materials as watery solutions obviously already takes place. At that stage probably hot waters would carry out from the sediment of, say, clay-composition, alkalies (mainly potassium) and silica, possibly also alumina (as alumosilicates). There, then, already exist hydrothermal solutions which may be moved for considerable distances, or, to some extent, also stay in the sediments forming microcline veinlets or scattered grains in recrystallized sediments, which still and always 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). Such schists have been interpreted as 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,) and these may also occur there as lenses and clusters within and conformably in the sulphide-graphite schists. Because there are no distinct granites in the vicinity, a possible explanation for this is that the pegmatites have derived from the sapropels due to expulsion of alkalies and quartz with waters under hydrothermal conditions.

The sapropels themselves have thereby been impoverished in potassium and silica, but they still contain much potassium which, if palingenesis for instance has occurred, could easily yield granite composition. This is true not only for the original sapropels of pelitic, but also of calcareous composition and also for similar rocks from 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 of the Outokumpu copper mine region, found also black schists short in potassium; on average, however, also there analyses with Na_2O 1.09 % to 1.97 % and K_2O 1.70 % to 3.14 % respectively commonly occur, the pegmatites being conspicuously less abundant there than they are at Kaustinen.

If the movement of expulsed, hot solutions continues through the stages of the regional metamorphism, places of the lowest free energy — cracks, fissures, fold openings, etc., will be filled with such material crystallizing as aplites and pegmatites, as has obviously been the case in migmatized areas with 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 in 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 bears a close association with the migmatite areas.

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 in cases when the granite porphyry and quartz porphyry veins clearly indicate the existence of a magma of granite composition (Mehnert, 1959).

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.

There are, however, real granites with typical texture and composition, which do not fall into this category, and there the most characteristic constituent of the granites, potash feldspar, is definitely younger than the other constituents, and obviously metasomatically formed (p. 22 and 60). To this category belong the synkinematic rocks of granite composition (p. 21).

The true granite composition with equigranular texture and equal age of main constituents of the rock, however, are 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. 34).

For such granites, the present writer has adopted the following theory explaining their origin and emplacement. 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 as well, and, 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.

The field observations point out, however, that such an origin of granite is neither common nor widespread, because recrystallization of such sediments yields most usually a quartz diorite or granodiorite composition,

Table I

	1. Recent Litorina-clay. Vähäkyrö, Finland	2. Synkinematic granodiorite. Kameron, Sierra Leone	3. Synkinematic granite. Bumban, Sierra Leone
SiO_2	57.38	68.85	67.59
TiO_2	0.84	0.22	0.50
Al_2O_3	17.16	15.20	15.57
Fe_2O_3	3.23	1.58	0.99
FeO	4.17	1.27	2.50
MnO	0.09	0.05	0.04
MgO	3.03	0.84	0.58
CaO	1.71	3.83	2.64
Na_2O	2.19	6.15	3.76
K_2O	3.96	1.54	4.92
P_2O_5	0.28	—	0.20
CO_2	0.00	—	0.13
H_2O +	4.38	0.29	0.40
H_2O—	0.80	0.08	0.08
F	—	—	0.05
Cl	—	—	0.04
BaO	—	—	0.20
SO_3	0.14	—	S = 0.03
C	0.73	—	0.00
Total	100.09	99.90	100.32
Normative:			
albite	18.29	38.00	32.00
potash feldspar	23.30	8.50	23.70
anorthite	8.34	13.00	7.00
quartz	15.50	28.00	23.80
rest.	34.66	12.40	13.82
Total	100.09	99.90	100.32

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 obviously 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. 23) of sediments with local granitization phenomena will probably result. If, on the other hand, the regional metamorphism is accompanied by strong tectonic features 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, as well. This may explain to a large extent the formation of microcline granites.

But another kind of granite formation will certainly develop as well. Very many observations indicate that a palingenesis is a not infrequent phenomenon in the deep-seated rocks, including sediments. Also there (p. 65) partial re-melting may produce a granite composition, which would occur as granites very similar to those considered in the foregoing, although the orthoclase granites, in particular, must have been formed in this way (p. 50). But, in the opinion of the writer, also then both the palingenesis and emplacement must have taken place under hydrothermal conditions, and the accumulation of the material has been comparatively slow to enable the joint crystallization of potash feldspar and acid plagioclase:

— if the accumulation of granitic material to be crystallized is less sluggish, and the temperature somewhat elevated, the potash feldspar will crystallize predominantly as orthoclase which is also conspicuously perthitic, because under such conditions exsolution of 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 Al-Si framework into triclinic, there will appear triclinic spots 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, for instance, 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 vast majority of the latekinematic microcline granites, aplite cutting postkinematic orthoclase granites, microcline produced by granitization of synkinematic rocks or occurring as a replacement for plagioclase.

REFERENCES

BACKLUND, HELGE (1938) The problem of the rapakivi granites. J. Geol., vol. 46, p. 339.

—»— (1953) The granitization problem. Inst. Investig. Geol. »Lucas Mallada», Estudos geológicos, vol. 9, p. 71.

BARTH, TOM. F. W. (1952) Theoretical petrology. New York and London.

—»— (1956) Studies in gneiss and granite, I and II. Skr. utg. Norske Vidensk.-Akad. Oslo 1956, I, Mat.-Nat. Kl.

BOTT, M. H. P. (1957) A geophysical study of the granite problem. Quart. J. Geol. Soc. London, vol. 112, p. 45.

BOWEN, NORMAN L. (1947) Magmas. Geol. Soc. America Bull., vol. 58, p. 263.

—»— (1954) Experiment as aid to the understanding of the natural world. Proc. Acad. Nat. Sci. Philadelphia, vol. 106, p. 1.

BUDDINGTON, A. F. (1959) Granite emplacement with special reference to North America. Geol. Soc. America Bull., vol. 70, p. 671.

CHAYES, F. (1952) The finer-grained calcalkaline granites of New England. J. Geol., vol. 60, p. 207.

DALY, R. A. (1914) Igneous rocks and their origin. New York.

—»— (1933) Igneous rocks and the depths of the earth. New York and London.

EDELMAN, NILS (1956) Kallioperäkartan selitys 1033, Nötö. English summary: Explanation to the map of rocks. Geological map of Finland, 1: 100 000.

ENGEL, A. E. J. and ENGEL, CELESTE G. (1953) Grenville series in the Northwest Adirondack Mountains, New York. Pt. I, General features of the Grenville series. Geol. Soc. America Bull., vol. 64, p. 1013.

ENGELHARDT, WOLF VON (1961) Zum Chemismus der Porenlösung der Sedimente. Bull. Geol. Inst. Univ. Uppsala, vol. 40, p. 189.

ERDMANNSDÖRFFER, O. H. (1950) Die Entwicklung und jetzige Stellung des Granitproblems. Heidelberger Beitr. Miner. Petr., Bd. 2, p. 334.

ESKOLA, PENTTI (1914) On the petrology of the Orijärvi region in southwestern Finland. Bull. Comm. géol. Finlande 40.

—»— (1932) On the origin of granite magmas. Tschermaks Miner. Petr. Mitt., Bd. 42, p. 455.

—»— (1934) Über die Bottenmeerporphyre. C. R. Soc. Géol. Finlande 8, p. 111. Bull. Comm géol. Finlande 104.

—»— (1950) The nature of metasomatism in the processes of granitization. Internat. Geol. Congress, 18th session, Great Britain (1948), Repts., Pt. III, p. 5.

—»— (1955) About the granite problem and some masters of the study of granite. C. R. Soc. Géol. Finlande 28, p. 117. Bull. Comm. géol. Finlande 168.

ESKOLA, PENTTI (1956) Postmagmatic potash metasomatism of granite. C. R. Soc. Géol. Finlande 29, p. 85. Bull. Comm. géol. Finlande 172.

—»— (1960) Granitenstehung bei Orogenese und Epirogenese. Geol. Rundschau, Bd. 50, p. 105.

FERGUSON, R. B., TRAILL, R. J. and TAYLOR, W. H. (1958) The crystal structures of low-temperature and high-temperature albite. Acta Cryst., vol. 11, p. 331.

GOLDSCHMIDT, V. M. (1920) Geologisch-petrographische Studien im Hochgebirge des südlichen Norwegens. V. Die Injektionsmetamorphose im Stavanger-Gebiete. Skr. utg. Vidensk.-Selsk. Kristiania 1920, I, Mat.-Nat. Kl., Bd. 2.

GOLDSMITH, JULIAN R. and LAVES, FRITZ (1954) The microcline-sanidine stability relations. Geochim. Cosmochim. Acta, vol. 5, p. 1.

GOÑI, JUAN C. (1961) O rapakivi Lauras — Jazidas metaliferas assocides — Lauras do Sul — Rio Grande do Sul — Brasil. Esc. Geol. P. Alegre, Boletim 7, p. 1.

GORAI, M. (1951) Petrological studies on plagioclase twins. Amer. Mineralogist, vol. 36, p. 884.

GRANT, WILLARD H. (1953) Preliminary investigation of the relation of the granites to regional metamorphism in Hard County, Georgia. Geol. Soc. America Bull., vol. 64, p. 1531.

GUITARD, GÉRARD and LAFFITTE, PIERRE (1959) Les calcaires métamorphiques et les skarns du Pie de Costabonne (Pyrénées-Orientales). Sci. Terre, vol. 6 (1958), p. 57.

GUITARD, G., RAGUIN, E. and SABATIER, G. (1960) La symétrie des feldspaths potassiques dans les gneiss et les granites Pyrénées orientales. Bull. Soc. franç. Minér. Crist., tome 83, p. 48.

GYSIN, M. (1948) Les feldspaths potassiques des granites de Gestern et de quelques granites de l'Aar. Schweiz. Miner. Petr. Mitt., Bd. 28, p. 230.

—»— (1956) Sur la coexistence de l'orthose et du microcline dans un granite de l'Himalaya. Arch. Sci (Soc. Phys. et Hist. nat., Genève), vol. 9, p. 106.

HACKMAN, VICTOR (1905) Die chemische Beschaffenheit von Eruptivgesteinen Finnlands und der Halbinsel Kola im Lichte des neuen amerikanischen Systemes. Bull. Comm. géol. Finlande 15.

HIETANEN-MAKELA, ANNA (1953) Geochemistry of metamorphism (Abstract). Geol. Soc. America Bull., vol. 65, p. 1532.

HJELMQVIST, SVEN (1961) The relation between diabase, granite, and porphyry at Bullberget in Dalarna, Central Sweden; a proof of magmatic granite formation. Bull. Geol. Inst. Univ. Uppsala, vol. 40, p. 69.

HÄRME, MAUNU (1958) Examples of granitization of plutonic rocks. C. R. Soc. Géol. Finlande 30, p. 45. Bull. Comm. géol. Finlande 180.

—»— (1959) Examples of the granitization of gneisses. C. R. Soc. Géol. Finlande 31, p. 41. Bull. Comm. géol. Finlande 184.

—»— (1960) Kivilajikartan selitys B 1, Turku. English summary. General geological map of Finland, 1: 400 000.

HÖGBOM, A, (1928) On the relations between syntectonic granites and ore formation in Sweden. Fennia 50, No. 21.

JOHANNSEN, ALBERT (1941) Descriptive petrography of the igneous rocks, vol. II. Chicago.

KAITARO, SIMO (1953) Geologic structure of the late pre-Cambrian intrusives in the Åva area, Åland Islands. Bull. Comm. géol. Finlande 162.

KRANCK, E. H. (1931) Beiträge zur Kenntnis der Svecofenniden in Finnland II. Petrologische Übersicht des Küstengebietes E von Helsingfors. Bull. Comm. géol. Finlande 89.

KRANCK, E. H. and MCQUAIG, J. D. (1953) Experimental studies of rheomorphism. Geol. Soc. America Bull., vol. 64, p. 1446.

—»— and OJA, R. V. (1960) Experimental studies of an anatexis. Internat. Geol. Congress, XXI Session, Norden (1960), Pt. XIV, p. 16.

KULLERUD, GUNNAR and NEUMAN, HEINRICH (1953) The temperature of granitization in the Rendalsvik area, North Norway. Norsk Geol. Tidsskr., Bd. 32, p. 148.

KULONPALO, MAX and MARMO, VLADI (1955) Suomen molybdeenihohteista. Summary: On the molybdenite of Finland. Geologinen tutkimuslaitos. Geoteknillisiä julkaisuja 58.

LAITAKARI, AARNE (1918) Einige Albitepidotgesteine von Südfinnland. Bull. Comm. géol. Finlande 51.

LAITALA, MATTI (1961) Kivilajikartan selitys 2032, Siuntio. English summary: Explanation to the map of rocks. Geological map of Finland, 1: 100 000.

LAVES, FRITZ (1951) Artificial preparation of microcline. J. Geol., vol. 59, p. 511.

—»— (1952) Phase relations of the alkali feldspars II. The stable and pseudostable phase relations in the alkali feldspar system. *Ibid.*, vol. 60, p. 549.

MACKENZIE, W. S. and SMITH, J. V. (1959) Charge balance and the stability of alkali feldspars. Acta Cryst., vol. 12, p. 73.

MARMO, VLADI (1955) The petrochemistry of some Precambrian granites of West Africa and a petrochemical comparison with the Svecofennide granites of Finland. Amer. J. Sci., vol. 253, p. 391.

—»— (1956 a) On the emplacement of granites. *Ibid.*, vol. 254, p. 479.

—»— (1956 b) On the porphyroblastic granite of Central Sierra Leone. Acta Geographica (Helsinki) 15, No. 4.

—»— (1958 a) Orthoclase and microcline granites. Amer. J. Sci, vol. 256, p. 360.

—»— (1958 b) The problem of latekinematic granites. Schweiz. Miner. Petr. Mitt., Bd. 38, p. 19.

—»— (1959) On the TiO_2-content of magnetites as a petrogenetic hint. Amer. J. Sci., vol. 257, p. 144.

—»— (1960 a) On the potassium-argon-ages of the granitic rocks. Schweiz. Miner. Petr. Mitt., Bd. 40, p. 17.

—»— (1960 b) On the sulphide and sulphide-graphite schists of Finland. Bull. Comm. géol. Finlande 190.

—»— (1961 a) An example of granite obviously derived from rhyolitic material. C. R. Soc. Géol. Finlande 33, p. 137. Bull. Comm. géol. Finlande 196.

—»— (1961 b) On the albite of granitic rocks. *Ibid.*, p. 391.

—»— (1962) Geology of the Kangari Hills and of the area W of Mamansu. Geol. Surv. Sierra Leone, Bull. No. 2 (in press).

—»— and HYVÄRINEN, LAURI (1953) Molybdenite-bearing granite and granodiorite at Rautio, Finland. Econ. Geol., vol. 48, p. 704.

—»— and MIKKOLA, TOINI (1955) On the microcline of the granitic rocks of Central Sierra Leone. Schweiz. Miner. Petr. Mitt., Bd. 35, p. 287.

—»— and PERMINGEAT, F. (1957) A propos des feldspaths potassiques du granite d'Azegour (Maroc). Bull. Soc. franç. Miner. Crist., tome 80, p. 509.

MATISTO, ARVO (1961) Kallioperäkartan selitys 2213, Kuru. English summary: Explanation to the map of rocks. Geological map of Finland, 1: 100 000.

МАТКОВСКИЙ, О. И. (1956) Акцессорные минералы гранитоидов Осницкого комплекса Волыни. Львовский Гос. Унив., Львов.

MEHNERT, K. R. (1959) Der gegenwärtige Stand des Granitproblems. Fortschr. Miner., Bd. 37, p. 117.

MIKKOLA, AIMO (1949) On the geology of the area North of the Gulf of Bothnia. Bull. Comm. géol. Finlande 146.

MIKKOLA, ERKKI (1941) Kivilajikartan selitys B 7—C 7—D 7, Muonio—Sodankylä—Tuntsajoki. English summary: Explanation to the map of rocks. General geological map of Finland, 1: 400 000.

MÄKINEN, EERO (1913) Die Granitpegmatite von Tammela in Finnland und ihre Minerale. Bull. Comm. géol. Finlande 35.

NICOLAS, A. (1961) Combinaisons des macles Manebach-Baveno dans l'orthose du granite de Raon-l'Etape (Vosges). Bull. Soc. franç. Miner. Crist., tome 84, p. 287.

NYKÄNEN, OSMO (1961) Kivilajikartan selitys 1242, Korsnäs. English summary: Explanation to the map of rocks. Geological map of Finland, 1: 100 000.

ORVILLE, PHILIP M. (1961) Alkalimetasomatism produced by alkali ion exchange within a thermal gradient. Program 1961 Ann. Meet., Geol. Soc. America, Paleont. Soc., etc., p. 119 A (Abstract).

PARRAS, KAUKO (1958) On the charnockites in the light of a highly metamorphic rock complex in southwestern Finland. Bull. Comm. géol. Finlande 181.

PELTOLA, ESKO (1960) On the black schists in the Outokumpu region in eastern Finland. Bull. Comm. géol. Finlande 192.

PERRIN, R. and ROUBAULT, M. (1939) Le granite et les reactions a l'etat solide. Bull. Serv. Geol. Algérie, Ser. 5, No. 4, p. 64.

—»— (1950) Metamorphism of the Trias in the Alps. Geol. Mag., vol. 87, p. 89.

PETTIJOHN, F. (1949) Sedimentary rocks. New York.

PICHAMUTHU, G. S. (1961) Transformation of Peninsular gneiss into charnockite in Mysore State, India. J. Geol. Soc. India, vol. 2, p. 46.

Полевая, Н. И. (1956) Абсолютный возраст некоторых магматических комплексов в СССР по данным аргонового метода. Геохимия № 5, 1956, p. 43.

Полканов, А. А. (1955) О значении для геологии величин абсолютного возраста, определенных для минералов докембрия Карелии аргоновым методом. Тр. III сессии Ком. по опред. абс. возр. геол. форм., p. 85.

RAGUIN, E. (1957) Géologie du granite. 2me éd. Paris.

RAMBERG, HANS (1944) The thermodynamics of the earth's crust I. Preliminary survey of principal forces and reactions in the Earth crust. Norsk Geol. Tidsskr., Bd. 24, p. 98.

—»— (1952) The origin of metamorphic and metasomatic rocks. Chicago.

READ, H. H. (1948) Granites and granites. *In:* J. Gilluly, Origin of granite. Geol. Soc. America Memoir 28.

REYNOLDS, D. (1946) The sequence of geochemical changes leading to granitization. Quart. J. Geol. Soc. London, vol. 102, p. 389.

SAKSELA, MARTTI (1936) Über die geologische Kartierung und die Einteilung der Granite im finnischen Grundgebirge. C. R. Soc. Géol. Finlande 9, p. 275. Bull. Comm. géol. Finlande 115.

SATO, S. (1961) Some considerations on origin of granites, with special reference to the application and discussion of the Bowen and Tuttle's theory. Sci. Rept. Tokyo Kyoiku Daigaku, Sect. C, No. 70, p. 1.

SAVOLAHTI, ANTTI (1956) The Ahvenisto massif in Finland. The age of the surrounding gabbro-anorthosite complex and the crystallization of rapakivi. Bull. Comm. géol. Finlande 174.

SCHERMERHORN, J. L. G. (1960) Telescoping of mineral facies in granites. C. R. Soc. Géol. Finlande 32, p. 121. Bull. Comm. géol. Finlande 188.

SCHERMERHORN, J. L. G. (1961) Orthoclase, microcline and albite in granites. Schweiz. Miner. Petr. Mitt., Bd. 41, p. 13.

SEDERHOLM, J. J. (1912) Om palingenesen i den sydfinska skärgården samt den finska urbergsindelningen. Geol. Fören. Stockholm Förh., Bd. 34, p. 285.

—»— (1924) Granit-gneisproblemen belysta genom iakttagelser i Åbo-Ålands skärgård. *Ibid.*, Bd. 46, p. 129.

—»— (1925) The average composition of the Earth's crust in Finland. Bull. Comm. géol. Finlande 70.

—»— (1926) On migmatites and associated pre-Cambrian rocks of Southwestern Finland II. The region around Barösundsfjärd W. of Helsingfors and neighbouring areas. *Ibid.* 77.

—»— (1934) On migmatites and associated pre-Cambrian rocks of Southwestern Finland III. The Åland Islands. *Ibid.* 107.

SEITSAARI, JUHANI (1951) The schist belt northeast of Tampere in Finland. Bull. Comm. géol. Finlande 153.

SIMONEN, AHTI (1948 a) On the petrochemistry of the infracrustal rocks in the Svecofennidic territory of southwestern Finland. Bull. Comm. géol. Finlande 141.

—»— (1948 b) On the petrology of the Aulanko area in Southwestern Finland. *Ibid.* 143.

—»— (1953) Stratigraphy and sedimentation of the Svecofennidic early Archaean supracrustal rocks in Southwestern Finland. *Ibid.* 160.

—»— (1960) Plutonic rocks of the Svecofennides in Finland. *Ibid.* 189.

—»— (1961) Feldspar-equilibrium temperature of some Finnish rocks. C. R. Soc. Géol. Finlande 33, p. 367. Bull. Comm. géol. Finlande 196.

STEWART, D. B. (1959) Rapakivi granite from Eastern Penobscot Bay, Maine. Congr. Geol. Internat., XX Sesión, México (1956), Secc. XI-A, p. 293.

TUOMINEN, HEIKKI (1957) The structure of an Archean area: Orijärvi, Finland. Bull. Comm. géol. Finlande 177.

—»— (1961) The structural position of the Orijärvi granodiorite and the problem of synkinematic granites. C. R. Soc. Géol. Finlande 33, p. 499. Bull. Comm. géol. Finlande 196.

TUTTLE, O. F. (1952) Origin of the contrasting mineralogy of extrusive and plutonic salic rocks. J. Geol., vol. 60, p. 107.

—»— (1955) Geothermal gradients and granite magmas. Centre Natl. Recherche Sci., Colloque Internat. Pétrogr., Nancy, Sept. 4—11, 1955.

—»— and BOWEN, N. L. (1958) Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$—$KAlSi_3O_8$—SiO_2—H_2O. Geol. Soc. America Memoir 74.

WAHL, WALTER W. (1936 a) Om granitgrupperna och bergskedjeveckningarna i Sverige och Finland. Geol. Fören. Stockholm Förh., Bd. 58, p. 90.

—»— (1936 b) The granites of the Finnish part of the Swecofennian Archaean mountain chain. C. R. Soc. Géol. Finlande 9, p. 489. Bull. Comm. géol. Finlande 115.

WALTON, MATT (1955) The emplacement of granite. Amer. J. Sci., vol. 253, p. 1.

WEGMANN, C. E. (1930) Über Diapirismus. C. R. Soc. Géol. Finlande 3, p. 58. Bull. Comm. géol. Finlande 92.

—»— (1935) Zur Deutung der Migmatit. Geol. Rundschau, Bd. 26, p. 305.

WILKMAN, W. W. (1931) Beskrivning till bergartskartan C 4, Kajaani. Résumé en français. General geological map of Finland, 1: 400 000.

WILSON, N. W. and MARMO, VLADI (1958) Geology, geomorphology and mineral resources of the Sula Mountains. Geol. Surv. Sierra Leone, Bull. No. 1.

WINKLER, H. G. F. (1957) Experimentelle Gesteinsmetamorphose I. Geochim. Cosmochim. Acta, vol. 13, p. 42.

—»— (1958) Experimentell gebildete anatektische Schmelzen granitischer Zusammensetzung. Fortschr. Miner., Bd. 36, p. 55.

WYART, J. and SABATIER, G. (1956) Transformations mutuelles des feldspath alkalins. Bull. Soc. franç. Minér. Crist., tome 79, p. 574.

—»— (1959) Transformation de sédiments pélitiques à 800° C sous une pression d'eau de 1800 bars et granitisation. *Ibid.*, tome 82, p. 201.