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On the potassium migmatites of southern Finland

by Maunu Härme

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ON THE POTASSIUM MIGMATITES OF SOUTHERN FINLAND

BY

MAUNU HÄRME

WITH 31 FIGURES AND 7 TABLES IN TEXT AND ONE MAP

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ABSTRACT

Various Precambrian metamorphic and plutonic rocks in southern Finland have been strongly migmatized. The characteristic feature of these migmatites is their high content of additional potassium. The processes of metamorphic differentiation, partial anatexis, and diffusion of potassium have taken place in the front of migmatization. The main source of the additional potassium of the migmatites was an intrusive silicic magma. The magma originated in the depth; possibly its emplacement was connected with block movements of the crust.

INTRODUCTION

Sederholm (1907, p.110) originally defined the migmatites as follows: »For the gneisses here in question, characteristic of which are two elements of different genetic value, one, a schistose sediment or foliated eruptive, the other, either formed by the resolution of material like the first or by an injection from without, the author proposes the name migmatites». Sederholm thought that the »younger» component might be a product of anatexis *in situ* or — whether palingenic or juvenile in origin — might have invaded the »older» rock from an outside source. It has been stated that, in the controversy between Sederholm and Holmquist, the former considered all migmatitic veins of the Fennoscandian Precambrian complex to be arterites, whereas the latter interpreted them as venites. The situation was not so simple as that; both geologists admitted the existence of both possibilities (cf. Holmquist, 1920; 1921; Sederholm, 1913; 1923; 1926; 1934). They differed rather as to the generality and character of the two phenomena. Today many geologists accept a mere anatexis (segregation) *in situ* as the only source of the younger component of the migmatites. Although this seems often to have been the case, it is not necessarily the only possibility.

The original definition of the migmatites did not include any comment on the composition of the younger component. Mostly this consists of quartz-feldspar-bearing matter, i.e. it has a granitic or granitoid composition. Accordingly, the question of the origin of migmatites is connected with the mobility of the alkalies and, further, with the transformation to a granitic composition. In the Finnish Precambrian complex the formation of migmatites is mostly connected with the behavior of the alkalies, especially potassium. Therefore, the problems of granitization and transformation to a granitic composition in general cannot be avoided in the study of these migmatites.

During the last ten years I have investigated a number of details (Härme, 1958 a; 1959; 1962; Härme and Laitala, 1955) in the migmatite area of southern Finland. These studies, together with results obtained by other investigators — many details are presented in the papers cited — form the basis of the present paper. The purpose is to illustrate and summarize the main migmatite types and the principal migmatitic processes of southern Finland.

GENERAL STATEMENTS

When studying the different migmatite types of southern Finland in regard to the occurrence of potassium in them, the following facts must be kept in mind:

— There are numerous intrusions, sills, dikes and other bodies of coarse-grained potassium granite (5—6 per cent K_2O) which cut rocks of different origin and composition, e.g., quartzite and limestone (Fig. 1). Not all these granitic bodies can be products of metamorphic segregation *in situ;* a mobile melt of potassium-rich granite, however, would account for these features.

— On the present surface the gneisses of supracrustal origin mostly contain plagioclase, quartz and biotite; only some interstratified beds in leptite gneisses contain abundant primary potash feldspar. The amount of potash feldspar-bearing gneisses is very small as compared with the huge amounts of intrusive potassium granite.

— In many places different rocks, of both igneous and sedimentary origin, are found to pass over (in metasediments even in the direction of the bedding) into potassium-rich migmatites with a content of K_2O that may amount to 5—6 per cent. If the rock was primarily poor in potassium, such migmatite cannot be identical in composition with the primary rock; an addition of potassium must have taken place. The above-mentioned intrusive coarse-grained potassium-rich granite is the main source of the potassium.

FIG. 1. Dikes of coarse-grained potassium granite cut the bedding of limestone at Mustio limestone quarry.

From these considerations the following questions arise:

— What was the physical action of the potassium-rich intrusion in the wall rock?

— What was the chemical influence of the potassium-rich melt upon the wall rock, i.e., how did the potassium spread from the source into the wall rock (into the surroundings)?

— What was the manner of occurrence and the origin of the potassium-rich melt?

ANATECTIC PHENOMENA CAUSED BY INTRUSIVE POTASSIUM-RICH GRANITE

In an earlier paper the author (Härme, 1962) has presented an instance where the coarse-grained potassium-rich granite (9.05 per cent K_2O) had forcibly intruded into and injected a quartz-plagioclase-biotite gneiss. In part the intrusion followed the schistosity of the wall rock concordantly and formed veined gneisses, but in part it had also brecciated the gneiss. A gneiss xenolith (Fig. 2) contains small lenses and patches of plagioclase and quartz as a product of metamorphic segregation. At the border of the xenolith against the granite the placioclase and the quartz mobilized and exuded into the surrounding potassium granite melt. Therefore the borders of the xenolith are rich in biotite. Lastly the biotite partially altered into almandite and cordierite. Near the contact with the xenolith the potassium granite contains more plagioclase, quartz and almandite than do portions farther from the contact.

The potassium granite there has a truly intrusive character, and primarily the gneiss did not contain potash feldspar. Thus the possibility that the potassium granite is on the whole a product of metamorphic segregation is excluded.

A similar instance is presented in Fig. 3. The older rock component is a quartz diorite; its mineral composition is presented in Table 1. The quartz diorite is cut and in part brecciated by a dike of coarse-grained granite rich in potassium. At the contact with the potassium granite, the quartz diorite has a biotite-rich rim. The quartz

TABLE 1

Mineral composition of a quartz diorite (point-counting method). Järvenpää. Vanhakylä

Constituents	per cent
Plagioclase (An_{35-40})	46.7
Quartz	38.4
Biotite	14.4
Accessories	0.5
	100.0

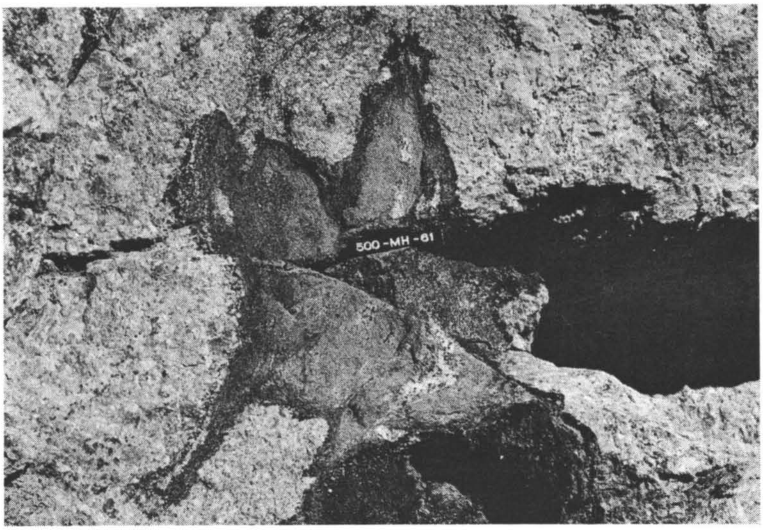

FIG. 2. Xenolith of plagioclase-quartz-biotite gneiss in coarse-grained potassium granite. The xenolith contains some small segregated patches of plagioclase and quartz. The biotite-rich rim around the xenolith is a rest from which plagioclase and quartz exuded into the intrusive potassium granite. At the borders of the xenolith the biotite was partly altered into almandite. Sipoo. Skräddarby. 1/10 natural size.

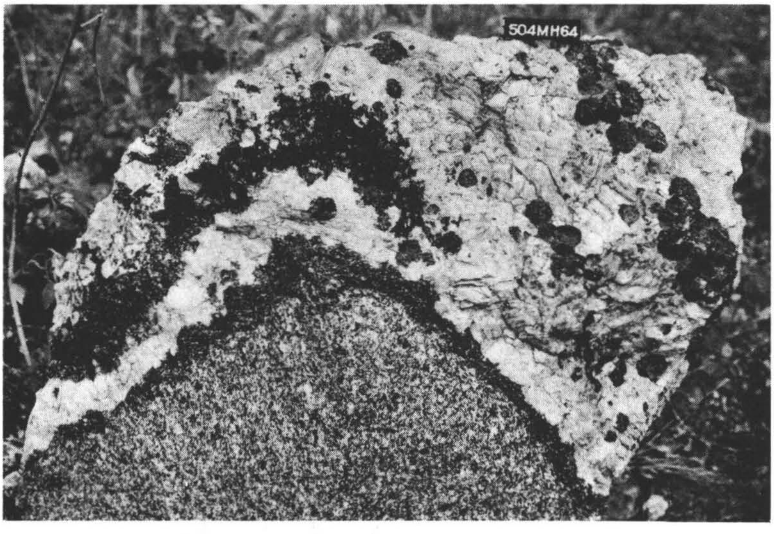

FIG. 3. Quartz diorite (below) cut by a dike of coarse-grained potassium granite. The biotite-rich rim against the dike is a rest from which plagioclase and quartz exuded into the potassium granite. The round dark spots in the pale-colored granite are almandite. The black band in the granite is an enrichment of biotite which was partly altered into almandite. Järvenpää. Vanhakylä. 1/6 natural size.

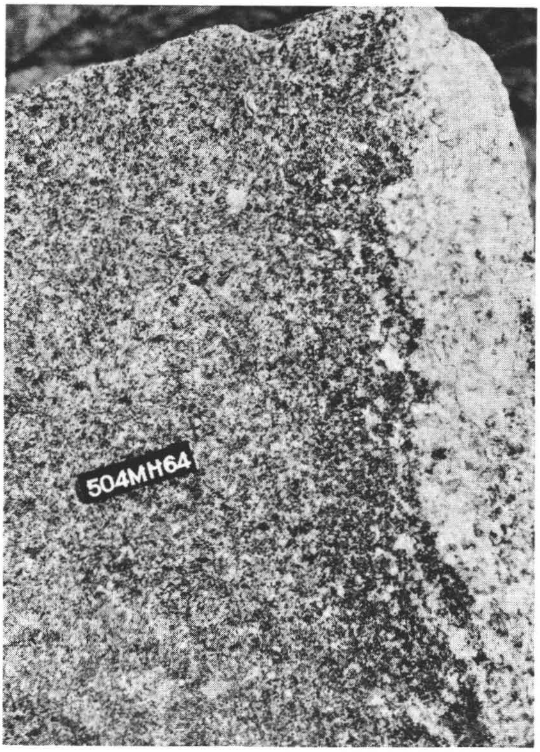

FIG. 4. A lenticular segregation (right) of plagioclase and quartz in quartz diorite. A slight, somewhat dark enrichment of biotite occurs in the quartz diorite against the segregation. Järvenpää. Vanhakylä. 1/4 natural size.

diorite is homogeneous but near the intrusive potassium granite it contains some small patches or lenses of quartz and plagioclase somewhat coarser in grain size (Fig. 4). The patches, too, are surrounded by a rim rich in biotite. Obviously the patches are segregations resulting from partial anatexis caused by the thermal action of the intrusive potassium-rich granite. The rim against the potassium granite is the rest that remained after the plagioclase and the quartz exuded into the potassium granite.

The intrusive potassium granite contains biotite-rich schlieren as rests of the quartz diorite. This biotite and the biotite of the contact rim were in part altered into almandite (up to 5 cm in diameter). The potassium granite is inhomogeneous (Fig. 5) and its average potassium content is roughly 5—6 per cent K_2O.

The primary quartz diorite does not contain potash feldspar, and only a part of the enriched biotite was altered into almandite. Its high content of potassium and

FIG. 5. A nebulitic coarse-grained dike of almandite-bearing potassium granite cuts quartz diorite (lower right). An enrichment of biotite occurs in the quartz diorite against the dike. Järvenpää. Vanhakylä. 1/9 natural size.

its truly intrusive character show that the potassium granite cannot be a product of metamorphic segregation *in situ*.

In the instances presented in the foregoing there is reason to suppose that the segregation of plagioclase and quartz took place in a melt, because a diffusion of the potassium from the dike into the wall rock should have occurred in the case of segregation through solutions.

A third example of potassium-rich migmatites is presented in Fig. 6. The mineral composition of the preserved portions of gneiss seen in the picture is presented in Table 2. In the outcrop the composition of the gneiss varies between this and a less

TABLE 2
Mineral composition of a gneiss (point-counting method).
Helsinki. Munkkiniemi

Constituents	per cent
Quartz	52.9
Plagioclase (An_{25})	32.5
Biotite	13.2
Potash feldspar	1.0
Accessories	0.4
	100.0

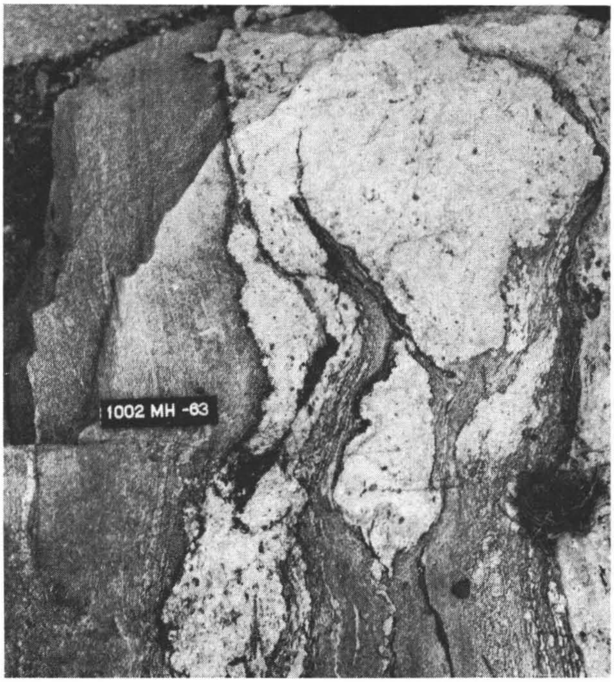

FIG. 6. Arteritic vein of coarse-grained potassium granite in quartz-plagioclase-biotite gneiss. Biotite-rich rests of the gneiss disappear into the granite. The gneiss has a biotite-rich rim against the granite. The small dark spots in the granite are almandite. Munkkiniemi. 1/8 natural size.

silicic one (up to gabbro-amphibolite). The dike of coarse-grained potassium granite penetrated the wall rock partly concordantly and partly discordantly. The gneiss frequently has a biotite-rich rim at its contact with the potassium granite, and in many cases, as in Fig. 6, it can be seen how some parts of the gneiss end in the granite as biotite-rich schlieren. Finally the biotite often altered into almandite. The chemical composition of the potassium granite in presented in Table 3.

Taking into consideration that some plagioclase and quartz moved from the gneiss into the potassium granite, it can be concluded that primarily the intrusive granite was richer in potassium and poorer in sodium and silica than the granite presented in Table 3.

A series of pictures of gneiss migmatites (Figs. 7—16) illustrates different migmatitic stages from preserved gneiss to a rock of granitic composition. The pictures are from different localities, because it was difficult to get a series of good photos from a single place. The phenomenon can be observed in many places, however. The characteristic feature of these migmatitic gneisses is the gradual increase of intruded

TABLE 3
Chemical composition of a potassium granite. Helsinki. Munkkiniemi.
Analyst. P. Ojanperä

Weight %		Weight norms		Niggli values	
SiO_2	77.04	qu	38.67	si	533.3
TiO_2	0.05	or	40.83	al	50.5
Al_2O_3	12.39	ab	16.58	fm	4.2
Fe_2O_3	0.15	an	0.31	c	1.6
FeO	0.27	en	0.42	alk	43.7
MnO	0.01	fs	0.31	qz	258.7
MgO	0.17	cor	1.57	k	0.70
CaO	0.22	mt	0.22	mg	0.42
Na_2O	1.96	il	0.10	o	0.02
K_2O	6.91	ap	0.28	c/fm	0.39
P_2O_5	0.12	CO_2	0.00		
CO_2	0.00	H_2O+	0.41		
H_2O+	0.41	H_2O-	0.06		
H_2O-	0.06				
Total	99.76		99.76		

and injected granitic matter and its action in the wall rock. The preserved portions of the gneiss sometimes contain a few obviously segregated veins of quartz or of quartz and feldspar (mostly only plagioclase) but metamorphic vein formation seems not to have taken place on a large scale in these gneisses before the action of the intrusive potassium granite.

The chemical composition of the final stage (Fig. 16) is presented in Table 5. The specimen analyzed contained only small amounts of cordierite and almandite.

The rock in question is a mixture of granite extremely rich in potassium and of quartz-plagioclase-biotite gneiss (cf. Table 4) assimilated by the granite. The gneisses presented in the pictures (Figs. 7—16) are of sedimentary origin and thus

TABLE 4
Estimated mineral composition of a preserved gneiss.
Lemu. Järäinen

Constituents	per cent
Quartz	49.7
Plagioclase (An_{35})	35.1
Biotite	11.4
Almandite	2.2
Accessories	1.6
	100.0

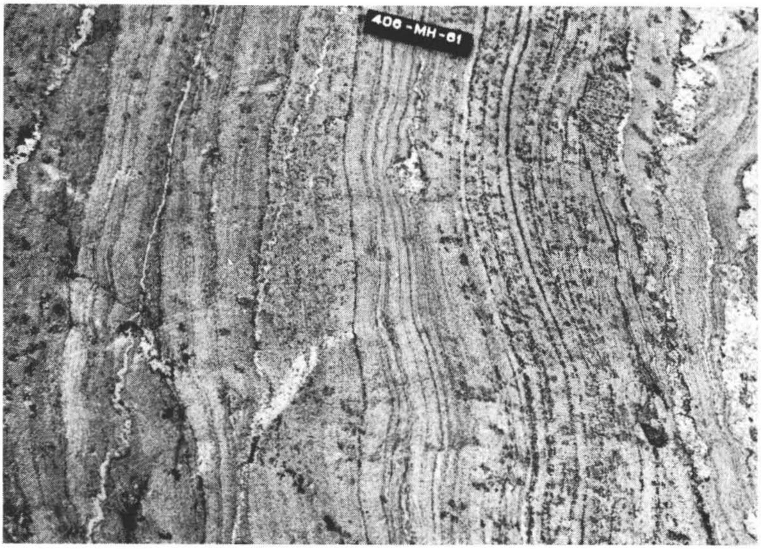

Fig. 7. Almandite- and cordierite-bearing quartz-plagioclase-biotite gneiss. The primary bedding is still visible. It was the sedimentogeneous excess of alumina that made possible the formation of the Al-rich minerals through metamorphism. Helsinki. Seutula airport. 1/8 natural size.

Fig. 8. Arteritic veins of potassium granite in quartz-plagioclase-biotite gneiss. Inkoo harbor.

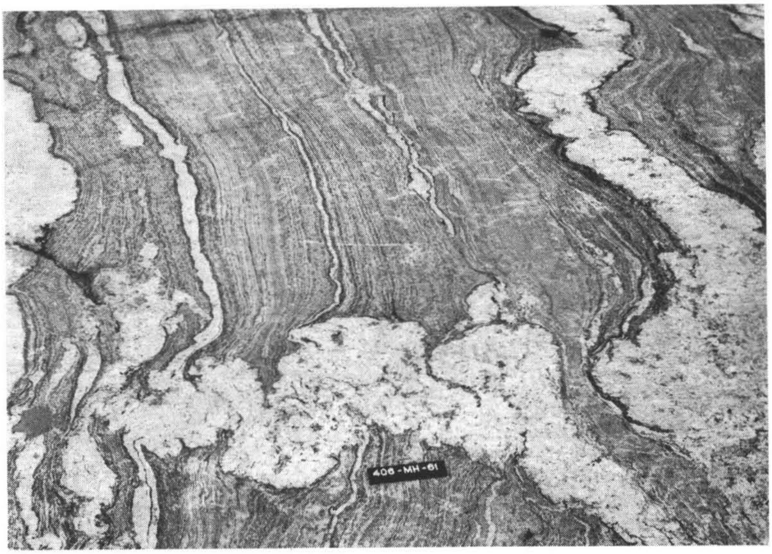

FIG. 9. Veins and dikes of coarse-grained potassium granite in quartz-plagioclase-biotite gneiss. Note the thin dark biotite-rich margins (rests) against the arteritic veins. Helsinki. Seutula airport. 1/12 natural size.

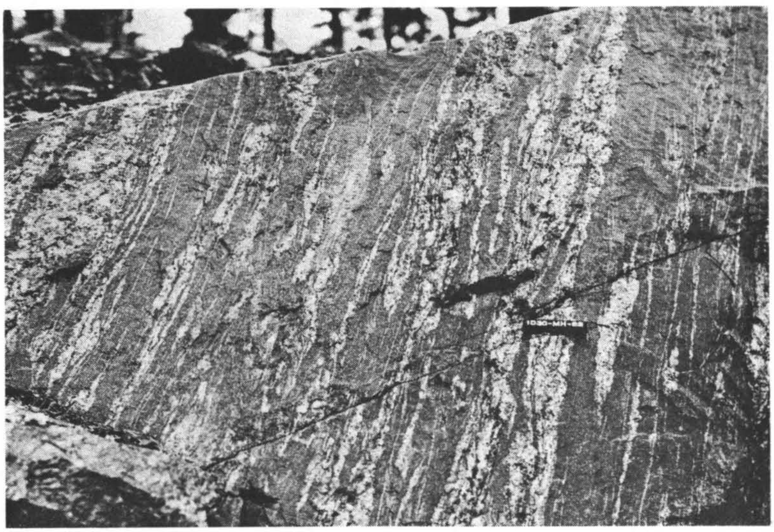

FIG. 10. Veins of coarse-grained potassium granite in quartz-plagioclase-biotite gneiss. The mineral composition of the unaltered gneiss is seen in Table 4. Lemu. Järäinen. 1/15 natural size.

FIG. 11. Veins of coarse-grained potassium granite in quartz-plagioclase-biotite gneiss. There is less gneiss than granite. Biotite-rich rests of the gneiss exist in the granitic portion. The dark spots in the granite are almandite and cordierite. Orimattila. Luhtikylä. 1/17 natural size.

FIG. 12. Biotite-rich rests of quartz-plagioclase-biotite gneiss in coarse-grained potassium granite. The dark spots in the granitic portion are almandite. Orimattila. Luhtikylä. 1/10 natural size.

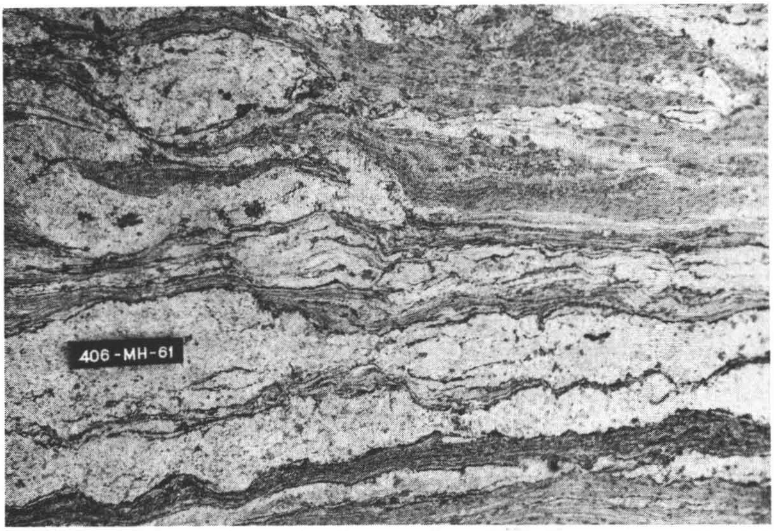

FIG. 13. Veins of potassium granite in quartz-plagioclase-biotite gneiss. The biotite-rich schlieren are rests from which plagioclase and quartz exuded into the arteritic granite. The dark spots in the granite are almandite. Helsinki. Seutula airport. 1/8 natural size.

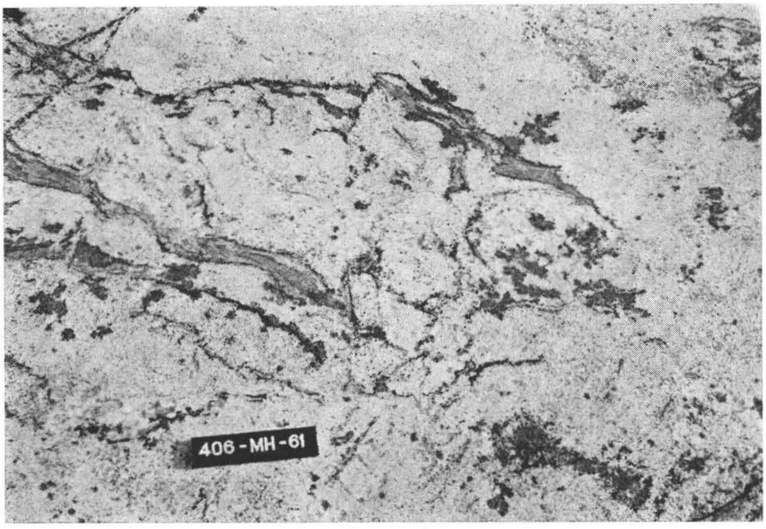

FIG. 14. Biotite-rich remnants of quartz-plagioclase-biotite gneiss in potassium granite. At the final stage the biotite was altered into almandite or cordierite (the dark spots). Helsinki. Seutula airport. 1/7 natural size.

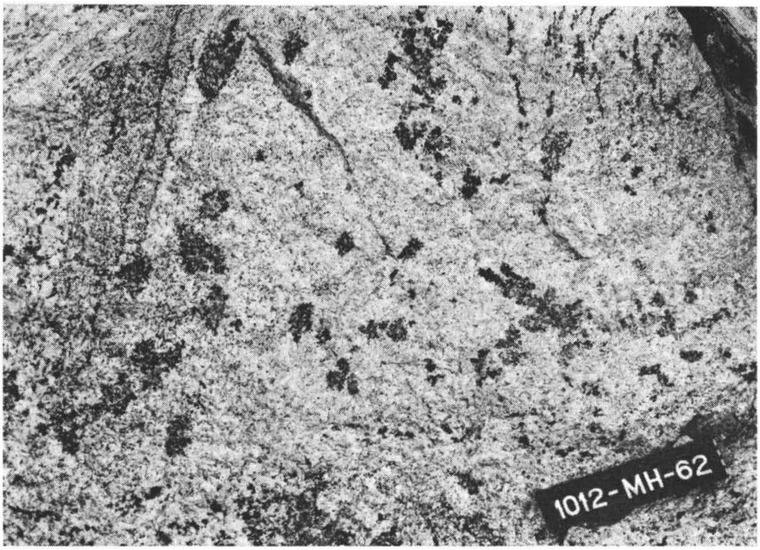

FIG. 15. Cordierite- and almandite-bearing (dark spots) potassium granite. The nebulitic biotite-rich streaks are remnants of a former quartz-plagioclase-biotite gneiss. Orimattila. Luhtikylä. 1/5 natural size.

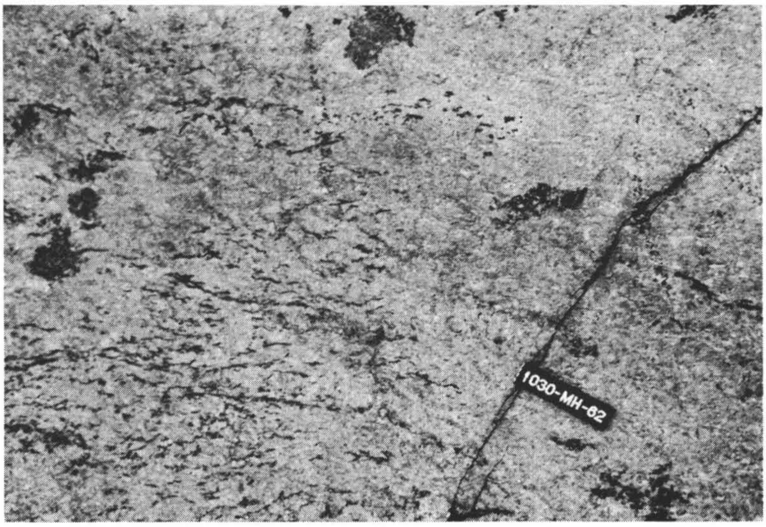

FIG. 16. Coarse-grained potassium granite. The dark spots are cordierite. Lemu. Järäinen. 1/9 natural size.

TABLE 5

Chemical composition of a potassium granite. Lemu. Järäinen. Analyst A. Heikkinen

Weight %		Weight norms		Niggli values	
SiO_2	75.03	qu	39.34	si	469.6
TiO_2	0.04	or	30.28	al	55.6
Al_2O_3	15.08	ab	20.30	fm	2.7
Fe_2O_3	0.04	an	4.12	c	6.7
FeO	0.16	en	0.41	alk	35.0
MnO	0.01	fs	0.20	qz	229.5
MgO	0.17	cor	4.08	k	0.58
CaO	1.00	mt	0.07	mg	0.65
Na_2O	2.40	il	0.08	o	0.09
K_2O	5.12	ap	0.30	c/fm	2.51
P_2O_5	0.13	CO_2	0.00		
CO_2	0.00	H_2O+	0.65		
H_2O+	0.65	H_2O-	0.04		
H_2O-	0.04				
Total	99.87		99.87		

their primary compositions varied somewhat in different bands. Characteristic of them all, however, is the lack of primary potash feldspar. It is very difficult to estimate the proportions of the two components in the granite analyzed. It can only be inferred that the potassium content of the intruded matter must-have been much higher than that shown by the analysis (Table 5).

In places the biotite-rich rim along the border of the gneiss against the granite was strongly altered into cordierite (Fig. 17) or other Al-rich minerals.

In all the examples presented, an intrusive potassium-rich granite acted upon the wall rock, causing a partial anatexis of its felsic matter (plagioclase and quartz), which then formed segregated patches, lenses or even veins in the wall rock. Near the contact the anatectic material exuded into the intrusive granite (primarily very rich in potassium), the composition of which became nearer to that of a normal granite (cf. Härme, 1962, p. 122). The potassium granite compositions presented in Tables 3 and 5 must be regarded as representative of the compositions of a hybrid (composite) melt.

In the instances presented the potassium-rich granite is characteristically very coarse-grained, like a pegmatite. In such cases where it obtained additional quartz and plagioclase from the wall rock, its grain size is essentially smaller but still rather coarse (cf. Härme, 1962, p. 123).

The mobile character of the potassium granite is illustrated in Fig. 1. In the limestone quarry at Mustio the dikes of potassium granite cut the limestone layers. The contacts of the dikes are sharp, and skarn formation at the contacts is very weak. Because the limestone there is an interstratified bed in the sedimentogeneous gneiss

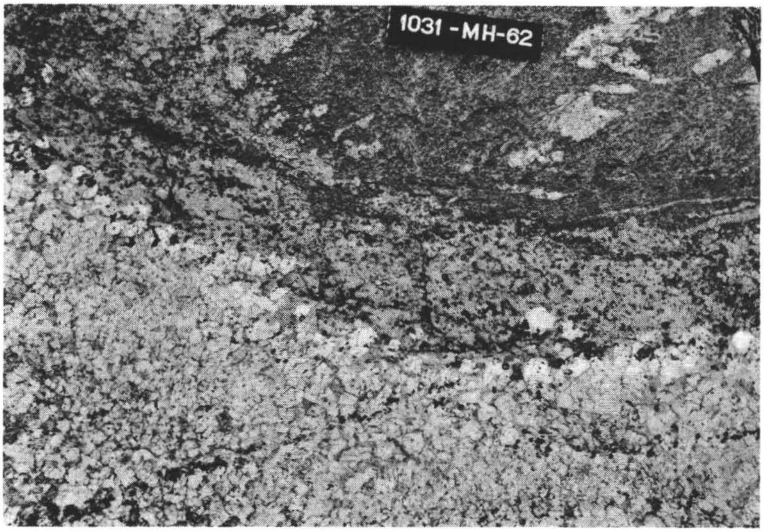

FIG. 17. A cordierite seam, about 10 cm thick, at the border of the quartz-plagioclase-biotite gneiss against coarse-grained potassium granite. Nousiainen. 1/6 natural size.

(Härme, 1954 b) the dikes must have cut the underlying gneisses and obviously also assimilated their material. Two chemical analyses (Table 6) have been made of these granitic dikes, one of them (1) of the most coarse-grained rock type and the other (2) of a variety with smaller grains.

TABLE 6
Chemical compositions of two varieties of the potassium granite. Mustio. Analysts (1) P. Ojanperä and (2) A. Heikkinen

Weight %			Weight norms			Niggli values		
	1	2		1	2		1	2
SiO_2	72.13	75.00	qu	21.70	32.29	si	377.1	455.5
TiO_2	0.05	0.06	or	48.28	38.41	al	47.6	48.1
Al_2O_3	14.64	13.45	ab	25.97	22.18	fm	5.1	5.3
Fe_2O_3	0.33	0.04	an	1.83	4.20	c	2.2	6.0
FeO	0.27	0.43	en	0.74	0.77	alk	45.1	40.6
MnO	0.01	0.01	fs	0.14	0.66	qz	96.6	193.0
MgO	0.30	0.31	cor	0.01	0.56	k	0.64	0.62
CaO	0.37	0.92	mt	0.48	0.07	mg	0.48	0.56
Na_2O	3.07	2.62	il	0.09	0.12	o	0.27	0.04
K_2O	8.17	6.50	ap	0.18	0.13	c/fm	0.43	1.14
P_2O_5	0.08	0.05	CO_2	0.00	0.15			
CO_2	0.00	0.15	H_2O+	0.28	0.43			
H_2O+	0.28	0.43	H_2O-	0.07	0.04			
H_2O-	0.07	0.04						
Total	99.77	100.01		99.77	100.01			

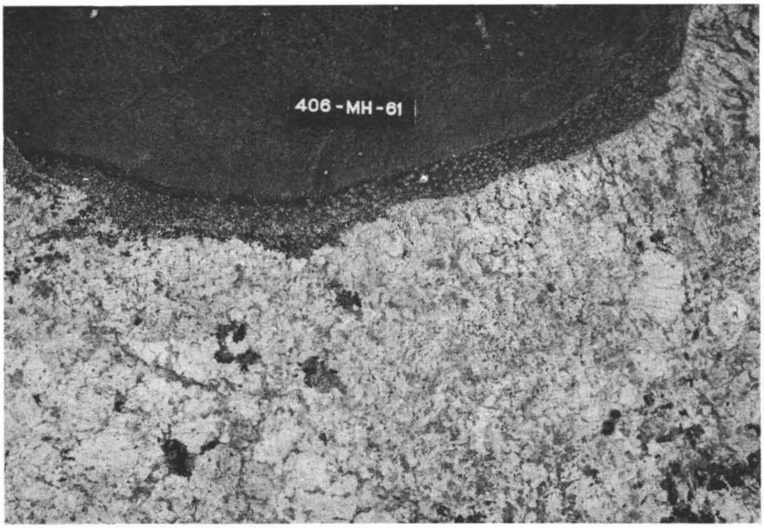

FIG. 18. Almandite-bearing biotite-rich rim at the border of a gabbro xenolith against coarse-grained potassium granite. Helsinki. Seutula airport. 1/7 natural size.

FIG. 19. Dikes of potassium granite in a quartz diorite. The dark spots in the pale-colored dikes are cordierite. Kerava. 1/10 natural size.

THE DIFFUSION OF POTASSIUM

In an earlier paper the author, together with Laitala (Härme and Laitala, 1955), presented an example of the alteration of a gabbroic rock into a garnet-bearing biotite-plagioclase-quartz rock. The alteration was caused by a migmatitic potassium granite. The diffused potassium had altered amphibole into biotite. Simultaneously the An content of the plagioclase had decreased and the aluminum thus released made the formation of almandite possible. The most essential changes in the chemical bulk composition were the addition of the potassium and the diminution of calcium, while the amounts of silica and alumina remained almost unaltered. In all probability the volatiles played an important role in this process.

Another similar instance is presented in Fig. 18. As a third example mention may be made of that reported by Lehijärvi (1957, p. 15). In that case a xenolith of pyroxene gneiss in potassium granite was surrounded by a rim rich in biotite and almandite.

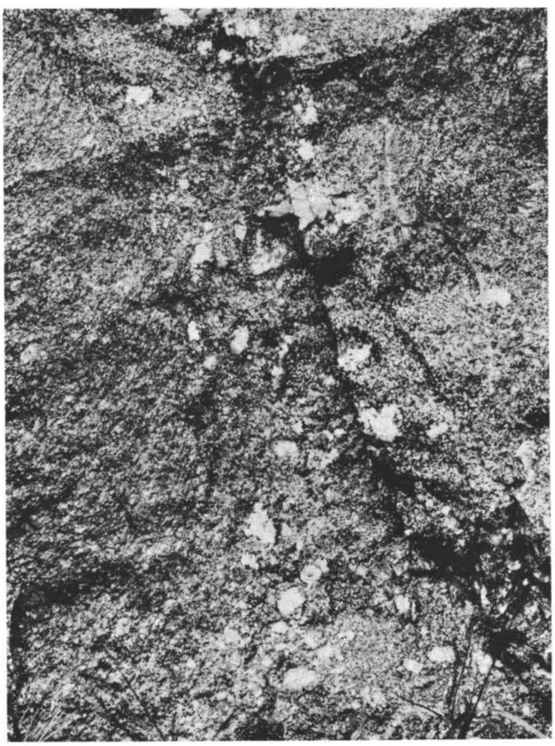

FIG. 20. Porphyroblasts of potash feldspar in a quartz diorite. The diffusion of the potassium followed a sheared zone. Järvenpää. 1/6 natural size.

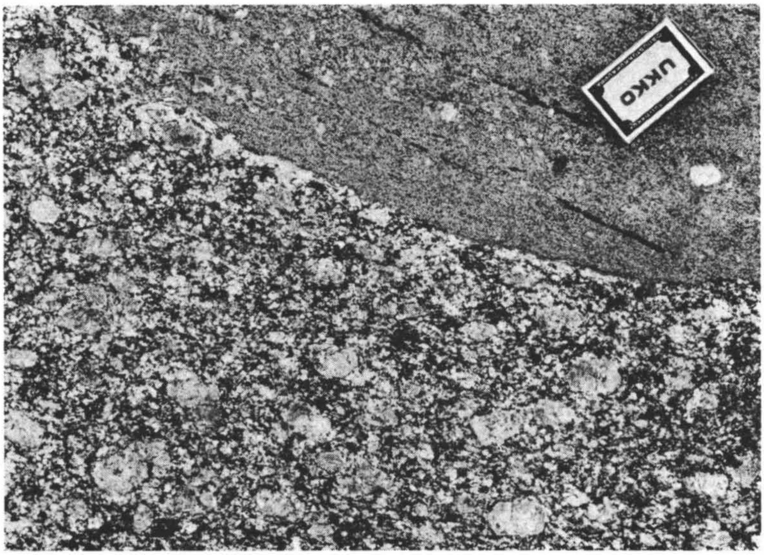

FIG. 21. Porphyroblasts of potash feldspar in granodiorite. Some porpyroblasts also occur in a gabbroic xenolith (upper right). About 2 km NE of Metsämaa church. 1/4 natural size.

Previously the present author (Härme, 1958 a) described several examples of the metasomatic alteration of various plutonic rocks. In those cases the diffusion of potassium had rendered the composition of the rock more granitic. The last stages of this process have led to a content of 5—6 per cent K_2O. Cordierite and almandite have very often been formed in this metasomatic process (Fig. 19); an instance with the formation of sillimanite in quartz diorite is known (Härme, 1958 a, p. 57, Fig. 16, Pl. IV; cf. Saksela, 1925, p. 9; 1935, p. 15). Hence the occurrence of aluminum-rich minerals in a plutonic rock does not necessarily indicate a sedimentary origin of the primary rock.

The diffusion of potassium frequently causes the formation of porphyroblasts of potash feldspar in the wall rock (Fig. 20). Porphyritic rocks of granitic bulk composition are very common products of this metasomatic process (Fig. 21) (see Saksela, 1935, p. 27; 1953, p. 49; Simonen, 1941, p. 138; 1948 a, p. 45; Edelman, 1949, p. 73; Härme, 1949, p. 36; 1954 a, p. 28; 1958 a, p. 47; Eskola, 1952, p. 136; 1956, p. 90; Salli, 1953, p. 24; Marmo, 1956, p. 16; 1962, p. 20; Nykänen, 1960, Figs. 3—6). The host rock may have been of supracrustal or infracrustal origin. Hietanen (1947, pp. 1074, 1080) has described some garnet- and cordierite-bearing granites in Turku, the so-called Kakola granites, regarding them as granitization products of kinzigites. Potassium metasomatism has, however, changed, e.g., quartz diorites into rocks of similar granitic composition (Härme, 1958 a; cf. Gavelin, 1955, p. 93; Lundegårdh,

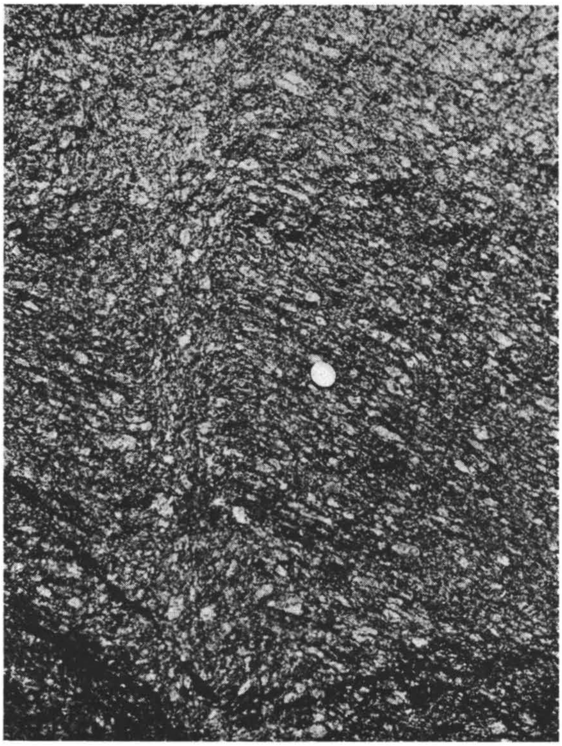

Fig. 22. Porphyroblasts of potash feldspar in quartz diorite. The orientation of the porphyroblasts follows the pre-existing schistosity of the rock. Siuntio. Karskog. 1/7 natural size.

1960, p. 59). In the most far advanced stage of this process the rock often contains 5—6 per cent K_2O (see, e.g., Salli, 1953, p. 22; Simonen, 1960, p. 68; Marmo, 1963, Table IX on p. 31). The porphyroblasts of potash feldspar are orientated in general along the pre-existing schistosity of the host rock (Fig. 22) (see Eskola, 1952, p. 129; Edelman, 1956, pp. 20, 37; Härme, 1959, p. 54).

An instance of the feldspathization of a quartzite (Fig. 23) was described by Härme (1959, p. 49). In that case not only did the potassium diffuse into the quartzite but addition of sodium, calcium and aluminum took place as well. The source of the invaded matter was a dike of coarse-grained potassium granite. The proportion of quartz decreased in the quartzite through the addition of feldspars. It is highly likely, although impossible to prove, that some silica migrated in the opposite direction. Otherwise an increase in the volume of the quartzite, caused by the metasomatism, must be assumed to have occurred. An increase in volume during the metasomatic processes is quite possible, however.

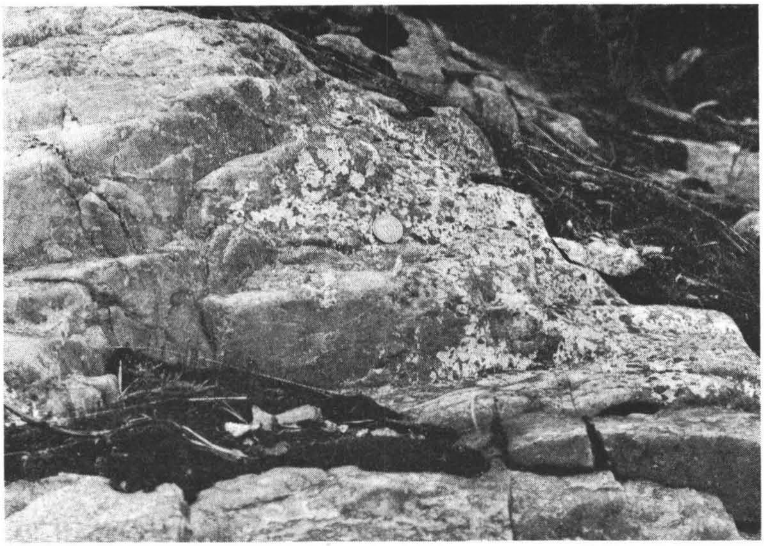

FIG. 23. Feldspathized quartzite. Kuopio. Puijo. 1/5 natural size.

An interesting example of the feldspathization of quartzite was presented by Gavelin (1960). A diffusion of sodium, calcium and alumina from a metabasite into the quartzite had taken place, causing plagioclase to form in the quartzite. Quartz is generally present in the metabasite, although it may be very irregularly distributed. It may have migrated from the adjacent siliceous sediment.

Not only the silicic rocks but also different subsilicic rocks (Fig. 24) in southern Finland have been affected by the potassium metasomatism. However, all the extreme rock compositions have been more resistant to the metasomatic action of the potassium-rich granite.

ON THE GRANITIZATION

Recently the term granitization has been used to mean »any process that renders a rock more like a granite» (see Sørensen ed., 1961, part Dietrich, p. 56). Usually in this connection the term granite also includes the »granitoids», i.e., silicic rocks in which the main feldspar is plagioclase. In addition, the granitoids may contain little or no potash feldspar, in consequence of which the total content of potassium is very low. This is not characteristic of true granite. If the granitoids are also taken into account, then the term granitization covers many processes differing totally in character.

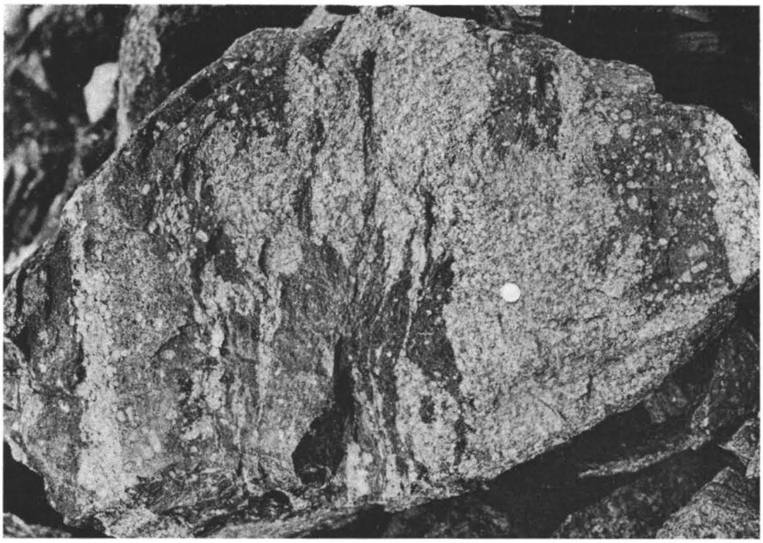

FIG. 24. Porphyroblasts of potash feldspar in gabbro xenoliths. Mäntsälä. 1/10 natural size.

It may be questioned whether we can speak about granitization if the process has not led to a truly granitic end stage. Do the chemical and/or mineralogical bulk compositions plus the texture suffice as criteria of a granite? What must be the dimensions of such a body? If the rock is a product of metasomatism, how much of the older component can the rock contain when it can be called a granite? As I see it, the term granitization embraces the secondary processes which could yield a true granitic end-product, even if the granitic end stage has not yet been reached.

ON THE PALINGENESIS

In the foregoing I have presented some simple examples of the principal processes involved in the formation of the migmatites in southern Finland: the diffusion of potassium into the wall rock, and the assimilation of the wall rock by the potassium granite (the process begins by the melting of the felsic constituents of the wall rock and ends in the total disappearance of the rests of the wall rock into the intrusive potassium granite). These phenomena are intimately linked. The effects of both are seldom to be seen in one and the same outcrop but are often visible in adjoining outcrops. Intermediate stages between these two main types occur, especially in the farther advanced phases of migmatization.

In connection with an abundant addition of potassium through diffusion, a partial melting often also took place in the wall rock. The partially melted rock mass was

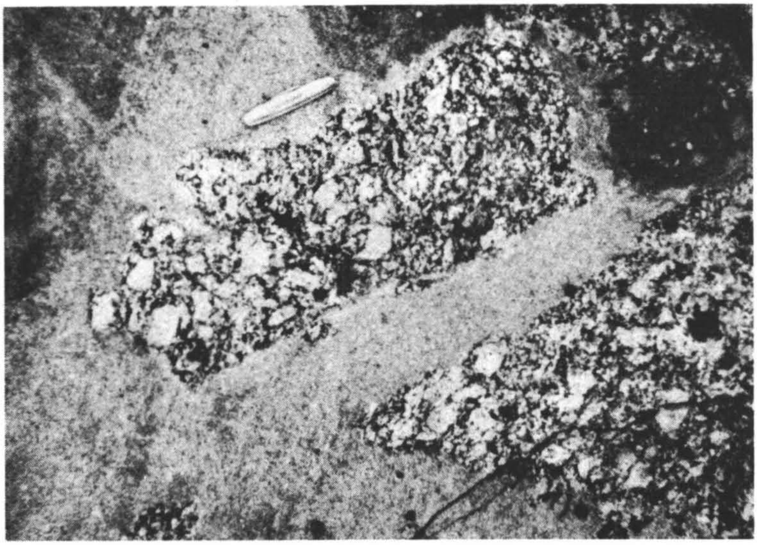

FIG. 25. Porphyroblasts of potash feldspar in quartz diorite (the xenoliths) subsequently brecciated by a palingenic potassium granite. Korpilahti. 1/6 natural size.

plastic and was sometimes able to behave like an intrusive melt (Fig. 25). One such instance was presented by Eskola (1960, p. 112).

Usually, after diffusion and partial melting, a massive or only weakly orientated rock yielded a relatively homogeneous rock mass. A strong schistosity, on the other hand, favored forceful injection and in that case a veined gneiss often represents an intermediate stage between the original rock and a more homogeneous end product.

Such was the case in the genesis of the so-called Hanko (Hangö) granite (Fig. 26; cf. Sederholm, 1923). Primarily the rock was a weakly schistose quartz diorite (called by Sederholm a »grey gneissose granite») which locally contained some inclusions of gneiss or amphibolite. In the migmatization some smallish segregations of quartz and plagioclase formed, but on a larger scale a partial anatexis took place in connection with the addition of the diffused potassium. The total content of potassium in this inhomogeneous granite is so high (e.g., 5.85 per cent K_2O; Sederholm, 1912, p. 304) that addition of potassium must have taken place. A part of the biotite altered into almandite or cordierite, with release of some potassium; this reaction did not change the total content of the potassium, however.

The granitic melt formed through partial melting was a mixture; the bulk of its potassium originated outside the melting rock. Such potassium promoted anatexis, and so made possible the melting of the felsic constituents (plagioclase and quartz)

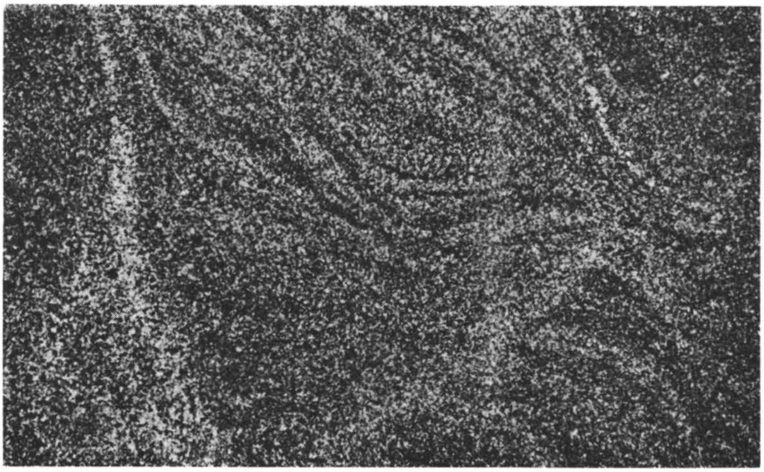

FIG. 26. Migmatitic granite of the Hanko (Hangö) type. The older rock component was quartz diorite. The light-colored schlieren are rich in potash feldspar. 1/8 natural size.

at a lower temperature[1] (cf. Härme, 1962, p. 122). The volatiles of the potassium granite certainly played an important role in this process. It might perhaps be better to call such a process a syntexis (cf. Sederholm, 1907, p. 49; Sørensen, ed., 1961, part Mehnert, p. 66) rather than an anatexis. The palingenic melt thus produced was able to behave like an intrusive magma. The potassium content of such a granitic melt is on an average 5—6 per cent K_2O (Eskola, 1956, p. 88).

In the area of Hanko granite there also exist some rock varieties, e.g., some porphyritic granites, which show no signs of partial mobilization. In those cases the high potassium content (up to 5—6 per cent K_2O) is a product of potassium metasomatism. Almandite and cordierite are common minerals in the Hanko granite (Sederholm, 1923, p. 99; Wegmann and Kranck, 1931, p. 62; Härme, 1958 a, p. 56).

In connection with the Hanko granite, Sederholm (1923, p. 49) described a structural feature which he called dictyonitic structure (Fig. 27). Along the former shear planes there are small granitic portions which Sederholm interpreted as products of remelting *in situ* during metamorphism. It is to be noted, however, that these granitic streaks are often rich in potassium. Here, too, an addition of potassium

[1] The biotite delivers its potassium as late as at the final stage of the partial melting process. Thus the melting temperature of the felsic constituents (plagioclase and quartz) of a quartz diorite is close to the minimum in the system Ab—Q—H_2O (cf. Tuttle and Bowen, 1960, Fig. 27). The diffused additional potassium shifts the composition toward that of the system Ab—Or—Q—H_2O, able to melt at a lower temperature.

An article by von Platen, »Experimental anatexis and genesis of migmatites», included in »Controls of metamorphism», edited by W. S. Pitcher and G. W. Flinn (Edinburgh and London: Oliver & Boyd, 1965), appeared during the printing of this paper.

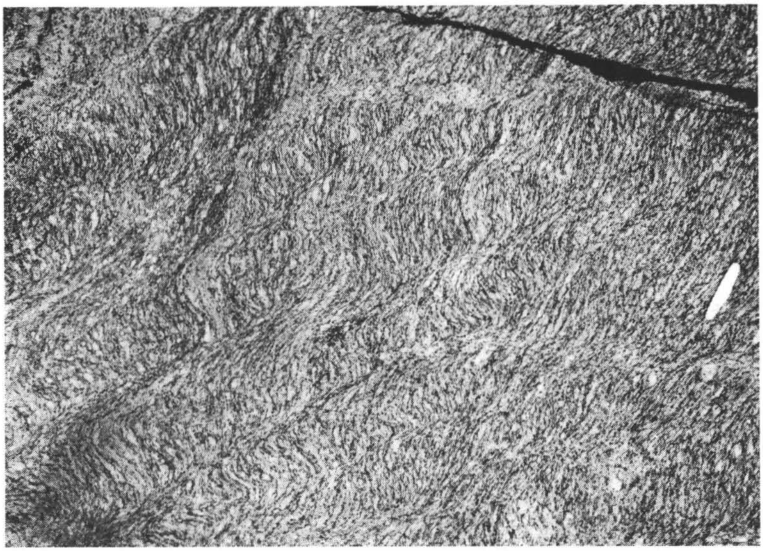

Fig. 27. Dictyonitic structure in Hanko granite. The rock is rich in porphyroblasts of potash feldspar. Hanko archipelago. Porsskär. 1/9 natural size.

facilitated the melting. The diffusion of the potassium took place most easily in the direction of the shear planes, with the result that the shear zones were peculiarly liable to undergo partial melting.

VEINED GNEISSES

In many cases a gneiss contained some almandite (Fig. 28) and/or cordierite (sometimes sillimanite, etc.) produced during normal regional metamorphism before the migmatization process. In these cases the Al-rich minerals reveal a sedimentogeneous excess of alumina in the rock. These gneisses very rarely contain potash feldspar or muscovite.

In connection with the vein formation subsequent to regional metamorphism, the amount of garnet and/or cordierite mostly increased. The biotite altered into almandite or cordierite and the potassium thus released could also be used to form potash feldspar. The free alumina needed was liberated from pre-existing compounds, e.g., the anorthite component of the plagioclase when the plagioclase altered into potash feldspar (Härme, 1958 a, p. 57; 1959, p. 47).

The author (Härme, 1959, p. 42) has previously described some examples of the changes in the mineralogical and chemical bulk composition which have taken place

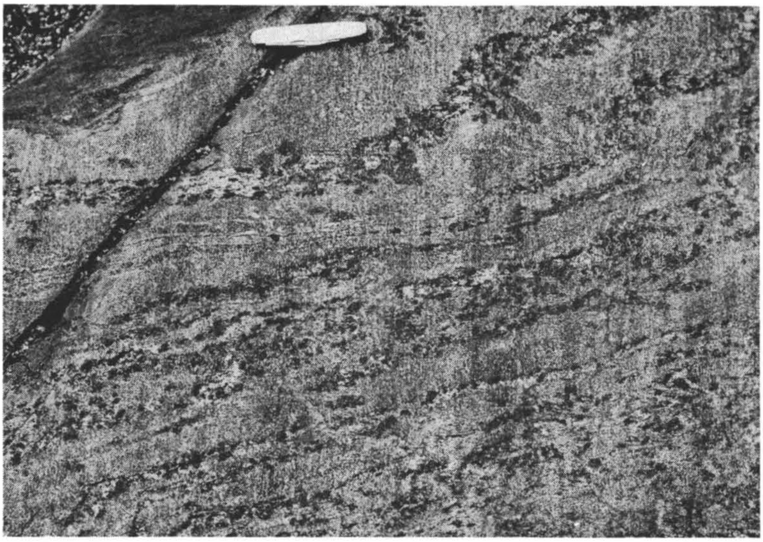

FIG. 28. Cordierite-bearing quartz-plagioclase-biotite gneiss. The dark streaks rich in porphyroblasts of cordierite follow the primary bedding. Helsinki. Malmi airport. 1/5 natural size.

in connection with the alteration of a regular gneiss into a veined gneiss. In these cases a strong addition of potash feldspar was characteristic (e.g., the total content of K_2O increased from 1.81 per cent to 5.39 per cent). In many cases the amounts of plagioclase and quartz diminished essentially. This may be due to the alteration of plagioclase into potash feldspar, a process caused mainly by the additional potassium. The amount of biotite decreased as well, because the biotite was partially altered into cordierite or almandite. Free silica was needed for this reaction.

A partial segregation of the felsic constituents (plagioclase and quartz) also causes the relative enrichment of the potassium in the paleosome. This process is not always, however, sufficient to explain the strong increase in the potassium content.

The total content of potassium in the densely veined gneisses is often much higher than in gneisses with no veinlets, even if both gneiss varieties primarily belonged to one and the same layer. Thus an addition of potassium must have taken place in connection with vein formation.

It is sometimes very difficult to decide whether the addition of potassium took place by diffusion of potassium or by injection of a potassium-rich melt. Intrusion and injection certainly occurred; in some preserved gneisses one can see thin veins (Fig. 8) which mostly follow the bedding of the gneiss but sometimes cut it (Fig. 9). The network of such veins and veinlets may be very dense; then the rock is a true veined gneiss.

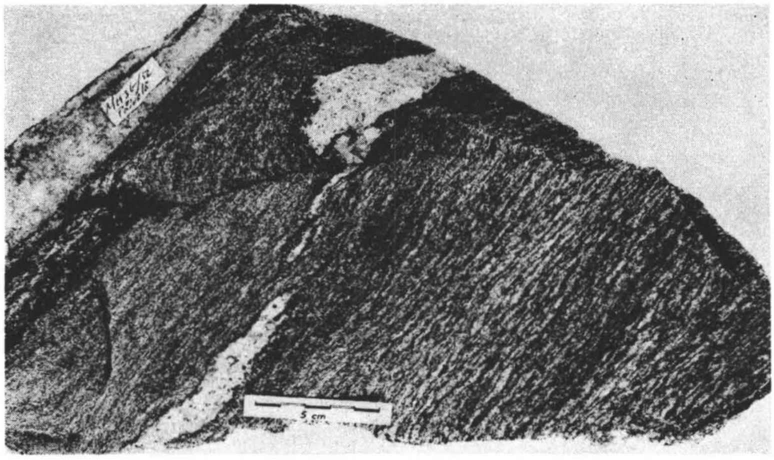

FIG. 29. Veined gneiss. The right-hand part of the specimen is densely veined. The thin veinlets are rich in potash feldspar and the spaces between the veinlets are rich in biotite. The left-hand part of the specimen contains some thicker veins of granite but the gneiss is better preserved and its content of potash feldspar is essentially lower. Degerby. Päivölä.

In other cases, however, the veinlets are so thin (the lit-par-lit structure; see Fig. 29) that they probably originated through diffusion of potassium along the planes of schistosity rather than as products of an injection of a potassium-rich melt. This diffusion of potassium (and the volatiles) then also promoted the partial melting of the plagioclase and quartz, and the melt segregated into thin veinlets. The biotite-rich spaces between the veinlets often contain abundant cordierite and/or almandite as products of the alteration of the biotite, and thus these spaces have the character of a restite. Often the chemical bulk composition of such veined gneiss contains much more potassium than could possibly have been released from the biotite, however.

Consequently, not all the veinlets of a lit-par-lit gneiss are of a true venitic character, because an addition of potassium had taken place. The source of the additional potassium was the intrusive potassium-rich granite. Usually it is very difficult to conclude which of the veinlets were injected and which were the result of segregation. It can only be stated that both vein types exist in one and the same area.

Presumably the volatiles of the intrusive potassium granite played an important role in the migmatitic processes. Sometimes the veined gneisses also contain sulphides which occur less frequently in the other gneisses.

At some localities it can be seen that at the time of vein formation the gneiss must have been very plastic (Fig. 30), a feature that strengthens the concept of partial melting. Sometimes the melt squeezed out from the veinlets to form patches or even aplitic dikes which cut the same gneiss. Thus some veinlets and dikes merely represent

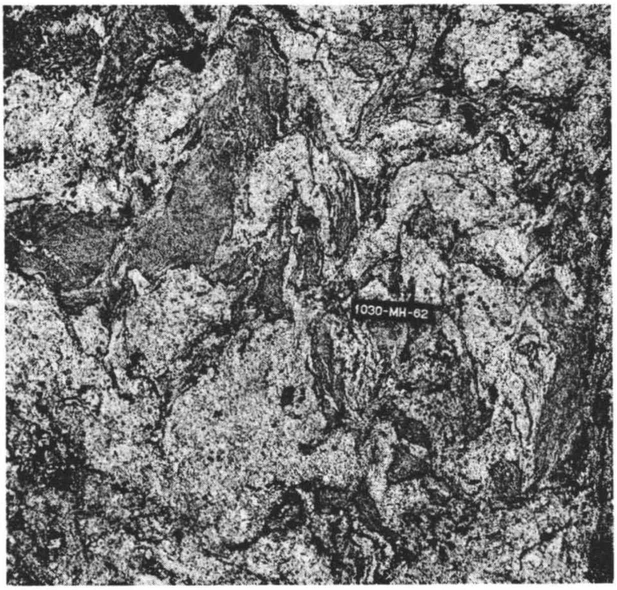

Fig. 30. Migmatite composed of potassium granite and quartz-plagioclase-biotite gneiss. The gneiss was partially melted, as shown by the biotite-rich schlieren (rests) in the granite, which also contains almandite. The bent forms of the gneiss portion show that the whole rock mass has been semiplastic. Lemu. Järäinen. 1/11 natural size.

different phases of one and the same process. Some of the garnet and cordierite may accompany the granitic component, but often they remain in the biotite-rich portions, which are thus restites or kinzigites (cf. Wimmenauer, 1950, p. 427; Mehnert, 1951, p. 182; Gavelin, 1953, p. 47). An instance is presented in Fig. 17. Wegmann and Kranck (1931, pp. 25, 62 and 89) have also stressed the rich occurrence of cordierite, almandite and other Al-rich minerals in the very zone of granitization.

Signs of later movements are very seldom to be seen in the veined gneisses. The densely veined gneisses occur in the same areas as those gneisses in which the felsic constituents partly melted and segregated as a result of the action of the intrusive potassium-rich granite. The two migmatite types occur irregularly in different outcrops but are intimately connected with each other.

In many localities it is possible to find a variety of stages ranging from a weakly veined gneiss to nebulitic potassium granite. Those migmatitic gneiss types that contain much granitic matter have been partially mobile (Fig. 30). From a consideration of the total potassium contents of the different migmatitic stages, we can conclude that the source of the potassium must have been near the partially mobilized portions and not on the opposite side, in the preserved gneisses. Consequently a potassium-rich granite intrusion

— caused partial melting in the wall rock, and
— sent intruded or injected veins into the wall rock. The potassium (and the volatiles) could have diffused further
  — forming, through metasomatic substitution, e.g., porphyroblasts of potash feldspar in the wall rock,
  — promoting, by the addition of potassium, the partial melting of the wall rock.

The melted material segregated and was able to form separate veins or small bodies, or it was exuded into the intrusive granitic melt.

THE MANNER OF OCCURRENCE OF THE POTASSIUM-RICH GRANITE

In southern Finland the potassium-rich granite has two principal modes of occurrence (see Appendix 1).

I. In some belts it has been truly intrusive and has brecciated, assimilated and injected the wall rocks. In this case the potassium-rich granite was connected with broad shear zones that crossed the belts of different rocks. Locally, however, its contacts may be concordant, as in the veined gneisses. Although the potassium-rich granite assimilated the wall rock, its dikes and bodies on the present earth surface still contain 5—6 per cent K_2O. Hence it must be assumed that its primary composition, before the assimilation, was much richer in potassium.

II. In some areas the diffusion of potassium took place on a large scale, and the most typical product of this process is a porphyritic granite. In this case the source of the potassium cannot always be deduced but often some scattered dikes show it to be the same potassium-rich granite. Diffusion on a large scale is commonest in the massive quartz diorites and granodiorites (Härme, 1958 a). The diffusion of potassium has often continued until the wall rock contained 5—6 per cent K_2O.

Locally, however, the diffusion of potassium has also taken place in the belts of the intrusive potassium granite, and some intrusions of potassium granite exist even in areas where the diffusion process dominated.

DISCUSSION

The diffusion of the potassium into the wall rock was a slow process, whereas the partial melting of the wall rock was obviously a more rapid one (Härme, 1962, p. 123). During the partial melting the temperature must have been higher than during the diffusion. Some signs, e.g., the alteration of pyroxene into amphibole and further into biotite (Härme, 1958 a, p. 56), show that water was present in the diffusion process. Most likely the diffusion of potassium could have happened in hydrothermal conditions (Eskola, 1956, p. 95; Simonen, 1960, p. 71; Marmo, 1962, p. 58; Härme, 1962, p. 123; cf. Mehnert, 1959, p. 180). Such a diffusion, especially the type that produced the porphyroblasts of potash feldspar, has taken place over wide areas, in true batholithic dimensions.

If the original composition of the wall rock was close to granitic (granitoids, some gneisses, etc.) it is fairly easy to verify the addition of potassium during the potassium metasomatism, but the changes in the content of the other elements are more difficult to trace. The contents of some important elements, such as Al and Si, were almost the same in the two rock components, the wall rock and the potassium granite, and probably their diffusion potentials were not very high. Furthermore, it is often impossible to draw exact conclusions as to what changes may have taken place in the rock volume during the metasomatic processes.

In the feldspathization of quartzite (Härme, 1959, p. 51) (Fig. 23) a noticeable addition of Ca and Al (besides that of the alkalies) took place. This is understandable, because in that case the diffusion potentials of those ions were also high.

The highest potassium content of the potassium granites hitherto known is 9.05 per cent K_2O (Härme, 1962, p. 116). A granite dike in Mustio (Table 6) contains 8.17 per cent K_2O. Metzger (1945, p. 66) has reported the potassium content of a migmatite granite to be 7.95 per cent K_2O. The commonest potassium content of these granites, however, is 5—6 per cent K_2O. This percentage corresponds to the composition of Eskola's (1950, p. 5; 1956, p. 89) »ideal granites» (later Eskola, 1963, p. 221, rejected the term and used the term kaligranite; see also Simonen, 1960, p. 71):

SiO_2	68—75 %
CaO	1—3 %
Na_2O	2—3 %
K_2O	5—7 %

The above composition does not represent the primary composition of the potassium granite but corresponds to the commonest end-product of the metasomatic or palingenic processes described in the foregoing pages.

It is difficult to explain why the metasomatic and palingenic processes caused by the potassium granite yield an end composition with such a high potassium content (5—6 per cent K_2O, 2—3 per cent Na_2O) (Fig. 31) as seems to be the case. One possibility may be that it represents the balance of the alkalies in the then prevailing physical conditions (see Orville, 1962, p. 301). This explanation is not indisputable, however. According to the experimental studies by Orville (1962; 1963), a diffusion of potassium from a granite intrusion into a cooler country rock can take place through the intergranular fluids. The potassium of the solutions can then replace the sodium of the Na-feldspar; potassium tends to migrate toward low-temperature

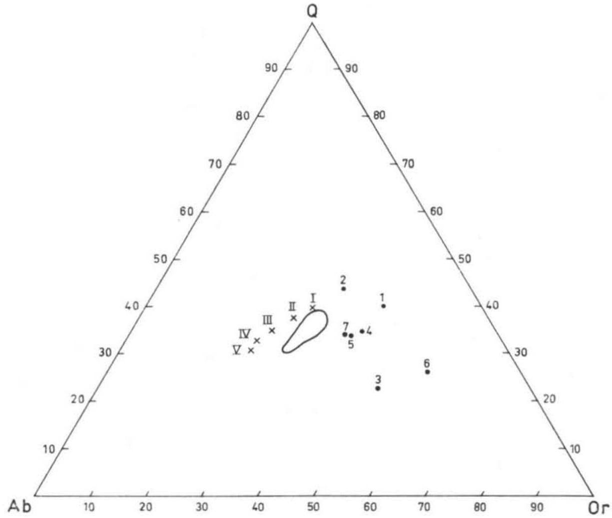

FIG. 31. Weight-normative albite-orthoclase-quartz ratios. 1. Potassium granite (Table 3), Munkkiniemi; 2. Potassium granite (Table 5), Lemu; 3. Potassium granite (Table 6, Column 1), Mustio; 4. Potassium granite (Table 6, Column 2), Mustio; 5. Average composition of potassium granites based on 18 analyses (Simonen, 1960); 6. Potassium granite (Härme, 1962); 7. Average composition of rapakivi (Sahama, 1945). Crosses: The positions of ternary minimums for various pressures of water-vapor, I. 500 kg/cm²; II. 1 000 kg/cm²; III. 2 000 kg/cm²; IV. 3 000 kg/cm²; V. 4 000 kg/cm² (Tuttle and Bowen, 1960, p. 75). The outlined area: The concentration maximum of granitic rocks.

regions and sodium toward high-temperature regions. Some examples (Simonen, 1941, pp. 128, 129; Krokström, 1946, p. 397; Ljunggren, 1956, p. 643; 1957, p. 130; Mísař, 1958, p. 287; cf. Mehnert, 1959, p. 146) nevertheless show that metasomatic sodium preceded the metasomatic potassium.

ON THE ORIGIN OF THE INTRUSIVE POTASSIUM-RICH GRANITE

It was stated in the foregoing that the potassium-rich granite of southern Finland is of a truly intrusive character. It occurs as numerous veins, as intrusive bodies and plutons. Its wall rocks (subsilicic rocks, quartz diorites, gneisses of greywacke composition, etc.) are mostly poor in potassium and usually their only potassium-rich mineral is biotite. Therefore, the huge amounts of potassium-rich granite cannot be segregations *in situ*. Some investigators consider it to be palingenic in origin. That is quite possible but then the source rock must have been beneath the present earth surface (see Eskola, 1955, p. 129; Simonen, 1960, p. 96).

Examples of the segregation of the potassium-rich granitic material on a small scale are known. Loberg (1963), for instance, has studied in detail lumps rich in potash feldspar occurring in meta-arenites at Västervik, Sweden. A corresponding process on a large scale may produce potassium-rich granitic matter, provided that the amounts of potassium-rich gneisses are large enough.

In southern Finland there occur some meta-arenites (quartz-feldspar gneisses, leptite gneisses) which also contain portions rich in residual potash feldspar. The amount of these potassium-rich gneisses is small, however, and therefore they cannot have provided an adequate source of the potassium-rich granites. A question apart is the origin of these potassium-rich meta-arenites; their material must have been derived from potassium-rich silicic plutonic rocks.

The less contaminated intrusive potassium-rich granite is coarse-grained and resembles pegmatite. As a rule, the richer the rock in potassium, the coarser the grain size, i.e., the less contaminated granite is coarser in grain than those varieties which contain more plagioclase and quartz. The differences in composition are revealed by the grain size.

The potassium-rich coarse-grained granite seldom contains rare minerals but outside its main intrusive zones there exist small bodies and dikes of typical complex pegmatites (e.g., the pegmatites in Kemiö and Tammela; Aurola, 1963). Some scattered observations show, however, that the intrusive potassium-rich granite was not quite devoid of rare elements. Dumortierite is met with in Kakola granite (Laitakari, 1934) and in the granite of Ruokolahti (Laitakari, 1949, p. 27). In many localities, e.g., at Korppoo (Laitakari, 1916), at Parainen (Laitakari, 1921) and at Silvola (Härme, 1965), the coarse-grained potassium-rich granite has caused skarn formation in limestone. In these cases the halogens and other volatiles of the potassium granite played an important role in the skarn reaction. One instance (Härme and Laitala, 1955, p. 98; cf. Härme, 1958 a, p. 56) shows that CO_2 took part in the reaction between potassium granite and gabbro. All these facts show that, in addition to water, the intrusive potassium granite melt also contained other volatile constituents.

Winkler and von Platen (1961 a and b) made experimental studies of the partial anatexis of different greywackes. »Die Untersuchungen ergaben, dass sich aplitische, granitische, granodioritische und tonalitische Schmelzen bilden können. In jedem Fall beginnt die Anatexis bei Temperaturen zwischen 670°C und 740°C bei 2 000 atm. H_2O-Druck mit der Bildung von aplitischen Alkalifeldspat-Quarz-Schmelzen, aus denen sich mit steigender Temperatur durch fraktionierte Aufschmelzung vor allem von Plagioklas kontinuierliche granitische, granodioritische und tonalitische Schmelzen entwickeln, welche dann auch einige Prozente an Mafiten gelöst enthalten.» . . . . »Entscheidend für den petrochemischen Charakter der anatektischen Schmelzen ist in erster Linie das modale, aus dem quantitativen Mineralbestand des hochgradigen Metamorphits feststellbare Verhältnis der Komponenten Albit zu Kalifeldspat, was völlig einleuchtend ist.» . . «Dies bedeutet, dass in der Regel mit steigendem Verhältnis der Gew-% Na_2O/K_2O der Metamorphite die anatektischen Schmelzen in der Reihe aplitisch bis tonalitisch voranschreiten» (Winkler and von Platen, 1961 b, p. 251).

Further *(op. cit.*, p. 252): »Grössere Komplexe von apliten sind nicht häufig zu erwarten, weil es nur wenige metamorphe Gesteine gibt, die ein so kleines Albit- zu Kalifeldspatverhältnis von < 0.4 haben, um ein aplitisches Endstadium zu bilden. Wenn auch alle Gesteine, deren Verhältnis Albit zu Kalifeldspat grösser ist, stets aplitische Schmelzen im Anfangstadium der Anatexis bilden, so werden diese keine grosse Bedeutung haben, weil (a) die Schmelzmenge noch recht gering ist, und weil (b) schon eine sehr geringe Temperatursteigerung von meistens 10—20°C, bisweilen auch 40°C, die aplitische Schmelze in eine granitische verändert.»

This means that only an extremely potassium-rich source rock can yield potassium-rich anatectic melt in great quantities. Such potassium-rich source rocks, e.g., gneisses, are not known to exist in sufficient quantities in southern Finland to account for the huge amounts of potassium granite there. Another possibility is that an unknown factor has taken away some sodium (and perhaps some silica) from the palingenic melt and led to a relative enrichment of potassium in the melt. The third possibility is that the thermal gradient in a large volume can cause a concentration gradient within this volume so that the potash feldspar is enriched in the cooler portion and the plagioclase in the hotter portion (see Orville, 1960, p. 309; see also Wahl, 1946).

A general trend in orogenic magmatism (e.g., Wahl, 1944, p. 212), especially in volcanism, must be taken into account, namely the fact that alkaline magmas are typical of the late- and postorogenic (kratogenic) phases. The potassium-rich granite is considered to belong to the late-kinematic phase, and, especially in southern Finland, the intrusion of its coarse-grained type (most potassium-rich) seems to have a connection with block movements (see Appendix 1). Hence one may suppose it to represent the early stages of the postorogenic alkaline magmatism.

The rapakivi granites in southern Finland are younger than the potassium granites, and they are considered to be postorogenic in age. An interesting fact is that the average composition of the rapakivi granites (5—6 per cent K_2O and 2—3 per cent Na_2O) is almost the same as that of the end-products of the metasomatic and palingenic processes caused by the potassium granite (cf. Simonen, 1948 b, p. 16; Eskola, 1950, p. 7). It is possible that these two granites have a common or at least analogous source of potassium. The instrusive potassium granite was slightly contaminated, its potassium content was high, and it reacted with the wall rock on a higher level. At later stage the same or a similar deep-seated potassium-rich melt reacted with the wall rock on a deeper level, producing a more homogeneous palingenic (syntectic) melt which then intruded upwards, forming the large plutons of the rapakivi granites.

North of the Tampere schist belt there is a wide area (about 10 000 km^2) of granitic and granitoid rocks. This area of the »central granites» (Sederholm, 1925) is not so coherent as presented previously. It encloses, for instance, lenses of metasediments as well as amphibolites of volcanic origin. Quartz diorites, granodiorites and granites dominate, however, in the area. Porphyritic granites and porphyritic (potash feldspar) granodiorites are common, and at many localities it can be observed that the phenocrysts of potash feldspar are porphyroblasts, i.e., products of potassium metasomatism (cf. Seitsaari, 1951, p. 89; Simonen, 1952, p. 36; 1960, p. 48; Marmo, 1963, p. 32).

An estimation of the crystallization temperature of the potassium granites is difficult. Simonen (1961) has made some calculations using the method developed by Barth (1956), and found that a potassium granite shows the feldspar-equilibrium temperature 450°C and an aplite 390°C. Some granite pegmatites range from 580° to 630°C. Mäkinen (1913) studied the same pegmatites and on the basis of the twinning of quartz he concluded that the crystallization temperature was about 573°C. The pegmatites studied are complex ones. A rapakivi granite (Simonen, 1961) gives a crystallization temperature of 730°C. These calculations do not take pressure into consideration.

Two separate problems are involved in the question of temperatures. One is the temperature of the intrusive potassium-rich melt and the other the crystallization temperature of the minerals, e.g., the feldspars. The former temperature might have been much higher than the latter. In addition, depending on the processes that the potassium granites underwent, some feldspars crystallized from the melt whereas others crystallized under hydrothermal conditions.

SUMMARY

The rock complex of southern Finland represents the root zones of a Precambrian mountain chain. Before the extensive phase of migmatization proper the rocks participated in orogenic folding and in regional metamorphism, which locally attained a high degree. Areas dominated by the amphibolite facies, pyroxene-hornfels facies and granulite facies are the results of that regional metamorphism. A subsequent migmatization then more or less changed the character of these areas. Thus, for example, the regional metamorphism yielded almandite- and cordierite-bearing gneisses but much of the almandite and cordierite were formed also in connection with the later migmatization.

In southern Finland the intrusive potassium-rich granite played the dominant role in the migmatization. It is possible that some migmatization, venitization and metamorphic segregation, was also caused by other factors, but this is very difficult to prove because the potassium migmatites now dominate in the whole area.

The principal processes involved in the formation of the potassium migmatites are presented in Table 7. The thermal action of the intrusive potassium-rich granite caused a partial melting in the wall rock. On the other hand, matter from the potassium-rich granite was injected and diffused into the wall rock, changing its composi-

TABLE 7

Scheme of the migmatizing actions of the intrusive potassium-rich granite in southern Finland

↑ Distance from the material and thermal source	*Feldspathized rocks*	Partial melting possible according to the pT conditions	*Veined gneisses*		*Palingenic magma*
	Feldspathization				
	Diffusion			Diffusion	
			Addition of new material (partial fusion, rheomorphism)		
	(Injection)		Venitic segregation (metatexis)	Injection (arterites)	Partial melting caused by thermal action. Assimilation (syntexis)
	(Intrusion; agmatite)			Intrusion	

Source of potassium and volatiles
Intrusive potassium-rich granite

tion. Obviously the volatiles (including water), which originated from the intrusive potassium-rich granite, played a significant part in these processes.

Palingenic magma. The thermal action of the intrusive potassium-rich granite melted the felsic matter, mostly plagioclase and quartz, of the wall rocks and of the xenoliths. The melt then exuded into the intrusive potassium-rich magma, rendering its composition richer in plagioclase and quartz and poorer in potash feldspar. The mafic minerals (biotite etc.) are either still to be seen as nebulitic schlieren in the granite or they have in most places altered into almandite or cordierite. The melt was thus composed of two constituents, intrusive magma and the wall rock matter assimilated by it. Usually the composite melt still contained 5—6 per cent K_2O and thus the primary intrusive magma must have been much richer in potassium (the highest known content of K_2O is 9.05 per cent, and then that of Na_2O is 1.87 per cent). This composite melt was still able to intrude.

V e i n e d g n e i s s e s. In the vein formation two kinds of processes took place through the action of the intrusive potassium-rich granite. Through intrusion and injection in a wall rock the potassium-rich melt formed a network (arterites) which may sometimes be very dense, and the chemical bulk composition of the mixed rock thus produced approaches that of granite. Some elements, especially the alkalies and volatiles, were able to diffuse further from these arteritic veins into the wall rock.

On the other hand, the thermal action caused partial melting in the wall rock, so enabling the melted felsic matter to segregate into the veins (venites). In connection with this process alterations of the mafic minerals may have taken place. The addition of the potassium and the volatiles diffusing in from the outside may have favored the melting of the felsic matter (mostly plagioclase and quartz).

In the veined gneiss formation of southern Finland the two processes were intimately linked. The segregated felsic matter exuded into the arteritic potassium-rich veins, making their composition more granitic. The biotite-rich rest may in part have remained unchanged or altered into Al-rich minerals, e.g., almandite or cordierite. Further, diffused potassium may have arrived in such amounts that it gave a granitic composition to the segregated felsic matter (mostly plagioclase and quartz). In some of the strongly veined gneisses the bulk content of K_2O may amount to 5—6 per cent.

From the foregoing it follows that the veined gneisses of southern Finland can not always be simply classified into arterites or venites.

Locally, the intruded or injected potassium-rich granite exceeded the gneissic wall rock in amount, and in such cases the granite assimilated all the gneissic portions. Biotite-rich nebulitic schlieren or alteration products are then the only indications of a former gneiss (Figs. 7—16).

F e l d s p a t h i z e d r o c k s. The potassium diffused from a potassium-rich granite intrusion into the wall rock and (in the case of quartzite, for instance, together with other elements) changed some of its minerals into potassium-bearing minerals. The commonest result was the formation of porphyroblasts of potash feldspar in the wall rock. In some places this feldspathization continued so far that the chemical bulk composition of the wall rock became granitic (K_2O may amount to 5—6 per cent). If the temperature rose high enough in connection with or after the addition of the potassium, the wall rock could melt partially, become plastic, and even intrude.

Mostly the feldspathization took place in massive or in only weakly orientated wall rock, and the process has also taken place on a large scale. Vein formation was more common in strongly schistose rocks. Strongly developed schistosity obviously favored the injection of the granitic matter in particular.

The processes described here, the diffusion and the partial melting, were able to occur in the same areas. The difference between the two processes was that the melting was a relatively rapid process and required a high temperature, whereas the diffusion was a slower process and could take place at a lower temperature.

Diffusion is a process which tends to eliminate the concentration differences. In all probability, the diffusion in the rocks did not take place in quite dry conditions. The diffusion in the rocks is not merely a migration of a single element in one direction but different elements can move in opposite directions. The different elements, however, have different diffusion velocities. On the other hand, a thermal gradient, for example, may have had an effect upon the concentration balance but its quantitative influence is not yet well enough known.

In the foregoing I have assumed the intrusive potassium-rich granite to be the thermal source. This is not the only possibility; other thermal sources may also have existed. At any rate, the potassium-rich granite was an intrusive melt, not a segregation *in situ*, and, on account of its high potassium content, its temperature must have been rather high. The addition of plagioclase and quartz changed its chemical composition toward that of a normal granite and, therefore, it could also stay melted at a lower temperature. It is likely, however, that in the milieu of these processes the thermal difference between the intrusion and the wall rock was not very great but the processes took place at relatively high temperatures.

The origin of the intrusive potassium-rich granite is uncertain; one can only conclude that the source was in the depth. It may be of palingenic origin but no other potassium-extreme rocks on the present surface level existed in quantities large enough to have yielded the huge amounts of potassium granite that exist in southern Finland. In broad outlines the occurrence of the intrusive potassium-rich granite follows certain shear zones in the Precambrian crust, and thus its intrusion appears to have been connected with block movements. Because of its manner of occurrence one may suppose the potassium-rich granite to be connected with the early stages of alkaline magmatism which are characteristic of late- and postorogenic phases.

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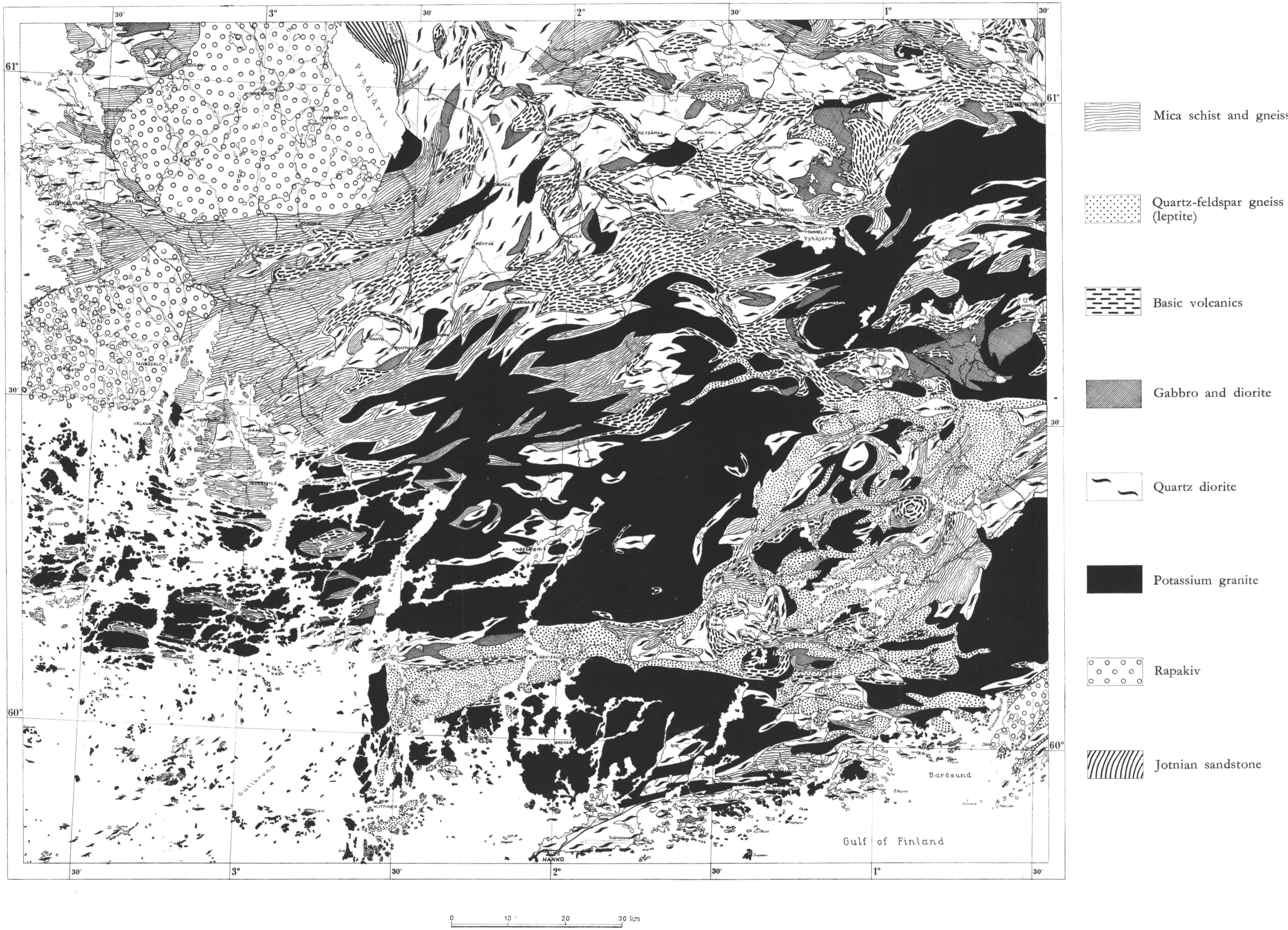

Simplified lithological map, scale 1:800 000, of southwestern Finland (Härme, 1958 b; 1960) The zigzag black belt from southwest to northeast (in the middle of the map) follows in general the combined en échelon faults in the E—W and SW—NE directions. In this zone the potassium granite is mainly intrusive. The black areas in the southeastern part of the map (north of Hanko and north of Barösund) are potassium granites which are mainly products of the diffusion of potassium. Primarily they were intrusive bodies of quartz diorite. The gneisses and quartz diorites, especially in the neighborhood of the potassium granite, are more or less migmatitic.