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Magnesia metasomatism at Hirvas, northern Finland

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MAGNESIA METASOMATISM AT HIRVAS, NORTHERN FINLAND

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WITH 11 FIGURES AND 4 TABLES IN THE TEXT AND ONE PLATE

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Previous field investigations of magnesia metasomatism have dealt with cases in which the primary unaltered rock was either unknown or inhomogeneous, stratified or composite. A new occurrence in northern Finland has been studied, where the metasomatically unaltered rock is a rather homogeneous metadiabase.

During metasomatism the metadiabase was transformed into cordierite-, anthophyllite- and/or cummingtonite-bearing rocks. Different stages of alteration have been found. Five chemical analyses were made to elucidate the changes in bulk compositions of the rock.

During the transformation process an addition of MgO, K_2O, SiO_2 and H_2O as well as a removal of CaO, Na_2O and Fe_2O_3 took place. FeO was mainly diminished but a local addition of it was found. A slight

decrease in the amount of alumina occurred during the beginning of the process but generally its amount remained nearly constant.

The metasomatism appears to have taken place without any volume change. No immediate cause of the metasomatism has been found in the field but the character of the chemical alteration process has much in common with that of metasomatic granitization.

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INTRODUCTION

The question whether magnesia metasomatism exists or not has for a long time been under discussion. In cases studied in the field it has usually been difficult to state the primary composition of the rock, and therefore the character of the alteration process has remained to some degree indistinct. Well known, however, are the works of Eskola (1914; Orijärvi region; SW Finland), Geijer (1917; 1921) and Magnusson (1936; Central Sweden). The later re-interpretations of Orijärvi region (Tuominen and Mikkola, 1950) have not been undisputable (see, Eskola, 1951, p. 93; Tuominen, 1951, p. 30).

Typical of the processes e.g. in the Orijärvi district is the metasomatic transformation of quartzo-feldspathic leptites into cordierite-antophyllite gneisses with complementary removal of calcium and sodium. Amphibolites were converted to cummingtonite amphibolites by exchange of magnesium for calcium in the original hornblende. Simultaneously with this magnesia-iron metasomatism local introduction of sulphides took place.

Some petrologists interpret basic (desilicated) contact zones of cordierite and antophyllite rocks as »basic fronts» enriched in magnesium expelled from the adjacent zone of granitization (e.g. Reynolds, 1946).

The present authors studied a Precambrian area at Hirvas in North Finland, where a basic rock was affected by metasomatic processes. In this case it is also possible to find the unchanged rock and thus verify the changes in bulk composition.

GENERAL OUTLINE

The Sukulanrakka hills (Fig. 1) are located about 4 kilometres SE of the village of Hirvas about 16 kilometres SW of the town of Rovaniemi and about 17 kilometres S of the Arctic Circle. Geologically the area is situated (Plate 1) in the so-called Kemi—Rovaniemi synclinorium of Precambrian age. The Rovaniemi sheet of the General Geological Map of Finland, by Hackman (1910), shows that a »metabasite» rock occurs there in rather wide areas together with sedimentogeneous quartzites. According to this map the nearest plutonic rock, a younger migmatitic potassium granite, lies at a distance of about ten kilometres NW of the Sukulanrakka hills. This granite was described by Hackman (1914, p. 34; see also Härme, 1949, p. 34).

FIG. 1. The Sukulanrakka hills as seen from southwest. In the foreground at the base of the hills are some outcrops of stratified arkosic quartzite (its beds face northwards). The quartzite is overlain by a metadiabase whose metasomatically altered derivates occur on the slope and on the top of the hills. — More than thirty glacial potholes have been found on the slope of the hill to the right of the kiosk.

The »metabasite» (later called metadiabase or greenstone) was later dealt with by Härme (1949, p. 13), who considered it to be a hypabyssal igneous rock of an early orogenic stage. The same rock kindred is quite common in the whole Karelidic zone (see, e.g., Eskola, 1925) where they occur as sills and lava flows. The parental composition was basaltic and most of the rocks of this magmatic kindred are spilitic with locally differentiated varieties like albitites and albite gabbros (see, Meriläinen, 1961).

The rocks of the Sukulanrakka hills are metadiabase and different derivates of its metasomatic alteration. The purpose of this study is to consider the mineralogical and chemical compositions at the different stages of metasomatic alteration in order to find out the character of that process.

In the vicinity of Sukulanrakka hills the general strike is about E-W, and across this direction the metadiabases and sedimentogeneous quartzites alternate (see outline map, Plate 1). The quartzite beds dip toward the North and the top, revealed by cross-bedding, is toward the same direction. Thus in the outline map area the metadiabase occurs as sills between bands of quartzite. This mode of occurrence is very common in the Kemi—Rovaniemi region as well as in the whole Karelidic zone.

Some younger diabase dikes cut the metadiabase in the Sukulanrakka area, and a few narrow irregular dikes or lenses of oligoclase pegmatite cut the metasomatically altered rocks.

FIG. 2. Metadiabase. Sukulanrakka hills. Hirvas, Rovaniemi. 5/8 natural size.

PETROGRAPHY

In the outcrops of Sukulanrakka hills it is possible to follow the gradual meta-somatic alteration of the metadiabase, and the present authors selected from here five specimens for microscopical study and chemical analysis. The samples were taken along increasing metasomatic alteration: number one (1) represents the meta-somatically unaltered metadiabase and number five (5) the most strongly meta-somatically altered rock. The specimens were taken across the southern border of the metasomatically altered belt for a distance of about 100 metres. All these rock types pass gradually over into each other without any sharp contact. It is possible that in the future more detailed field studies will reveal more compositional varieties but the purpose of this study is to clarify the trend of this metasomatism, i.e., what have been the changes in the total compositions during this process.

The primary, unchanged rock (specimen 1) which is a metadiabase (Fig. 2), contains somewhat more magnetite than the average metadiabase due to local varia-tions in magnetite content, however, it was the most suitable rock type situated nearest the altered rocks. There is no reason to suppose that the magnetite increased in this rock during metasomatism.

The second specimen (2) was taken at a distance of about five metres from the first (1). Megascopically its weathered surface resembles somewhat the unchanged meta-diabase (Fig. 3). The rock is still rather homogeneous and almost the same greenish color. The grain size is nearly the same but on the weathered surface laths of amphibole are discernible instead of those of the plagioclase as in the unchanged metadiabase (1).
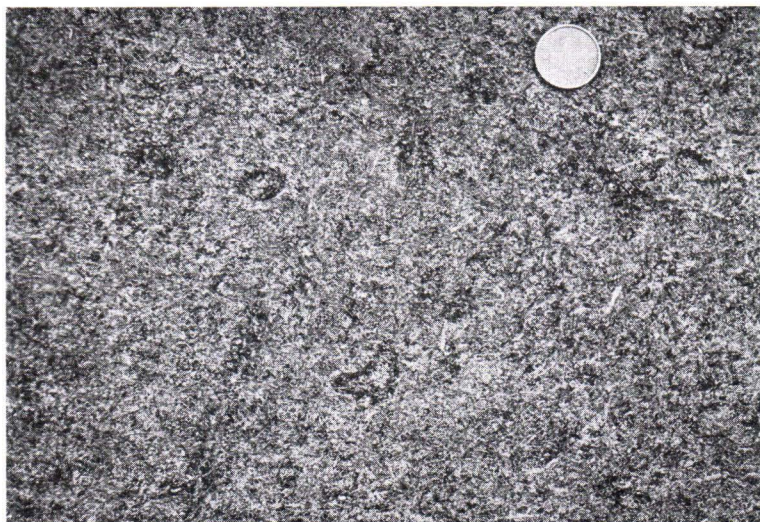
FIG. 3. Metasomatically altered metadiabase, type specimen 2 in the text. Sukulanrakka hills. Hirvas, Rovaniemi. 5/8 natural size.

The metadiabase (specimen 1) passes gradually into the altered rock (specimen 2) in a zone (less than one meter broad) where the rock is schistose, and the schistosity may be in part younger than the metasomatic alteration. No sharp contact is to be seen in this zone. On the other hand, there are indications that in the metasomatically altered areas, the metadiabase has been to some degree deformed before the alteration. These movements may also have continued weakly in the border zones during and after metasomatic alteration.

The third type specimen (3), taken further away from the unaltered metadiabase, has a weathered surface which reveals porphyroblasts of cordierite (Fig. 4). In some places the cordierite porphyroblasts may be up to 30 centimetres long (Fig. 5). Often the cross section of these porphyroblasts is a star with six branches (Fig. 6). It is not, however, a sixling but a single crystal, and encloses innumerous grains of amphibole, chlorite, biotite, quartz, ilmenite and feldspar. Due to the big porphyroblasts it is self-evident that the modal analysis of the third specimen could hardly be accurately determined.

The fourth type specimen (4) is a strongly changed variety, which megascopically gives the impression of a rather basic composition.

The fifth specimen (5) has been chosen in the field to represent the most advanced alteration. Rocks containing chloritized pseudomorphs of large cordierite porphyroblasts (Fig. 7) belong to this chlorite-rich alteration type, and confirm field observations that this chlorite-rich type represents a product of subsequent alteration. This rock type has often an orientated structure, and sometimes it is truly schistose but not cataclastic. Thus the deformation was most likely pre- or paracrystalline.

Fig. 4. Porphyroblasts of cordierite on the weathered surface of the metasomatically altered rock; it corresponds to type specimen 3. Sukulanrakka hills. Hirvas, Rovaniemi. 3/7 natural size.
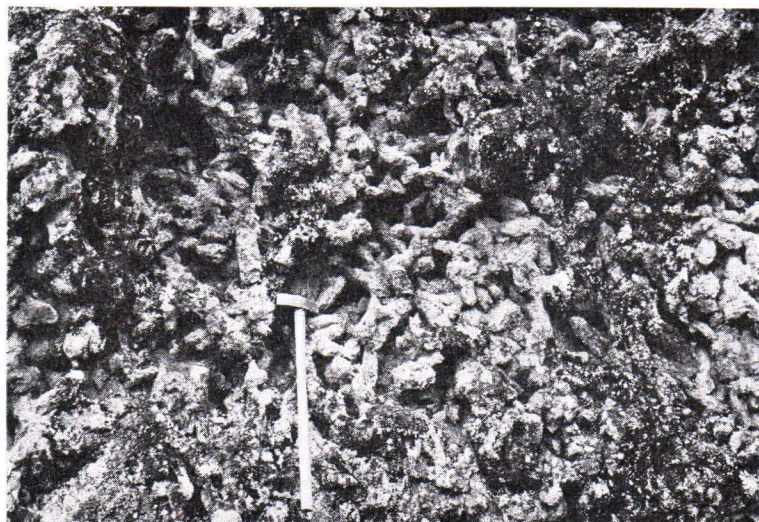
Fig. 5. Big porphyroblasts of cordierite on the weathered surface of the metasomatically altered rock. Sukulanrakka hills. Hirvas, Rovaniemi. 1/20 natural size.

FIG. 6. A star-like cross section of a cordierite porphyroblast. Sukulanrakka hills. Hirvas, Rovaniemi.

FIG. 7. Chloritized pseudomorphs (dark) of large cordierite porphyroblasts in the chlorite-rich metasomatically altered rock. Sukulanrakka hills. Hirvas, Rovaniemi. 1/6 natural size.

FIG. 8. Banded structure in the metasomatically altered rock. The dark portions are more or less chloritized porphyroblasts of cordierite. Sukulanrakka hills. Hirvas, Rovaniemi. 1/3 natural size.

Even though the primary rock was a homogeneous metadiabase the metasomatically altered rock locally reveals streaky patterns (Fig. 8). In some places such streaks have been altered more than others. This confirms the opinion that movement deformed the metadiabase before or at the beginning of the metasomatic alteration, and that the structures produced controlled and favored the alteration process. It is then an open question whether the deformation has been much earlier than the metasomatism or if the same agents that have caused the metasomatism, have in the initial stage given rise to movements and deformation. The present authors are inclined to prefer the latter possibility. It is, however, evident that the metasomatizing agents originated from depth.

Small amounts of pyrite, chalcopyrite and pyrrhotite have been observed locally in the strongly altered rocks. In places also a weak enrichment of tourmaline is visible to the naked eye.

The primary unchanged rock (1) at Sukulanrakka is a metadiabase (albite diabase). Its main constituents are presented in Table 1. Plagioclase (An_7) occurs as clear subhedral laths, with lengths of 0.3—3 millimetres. Pale-colored, yellowish, and yellowish-green ragged grains of amphibole range 0.2 to 0.8 millimetres in diameter and enclose small grains of albite and quartz. The smallest amphibole grains are euhedral prisms, with $2V\alpha = 75°$, and compositionally they represent the tremolite-actinolite series. Magnetite occurs as corroded subhedral grains, which are 0.1—0.5 millimetres in diameter. Biotite occurs as small dark brown scales usually near the

TABLE 1
Mineral compositions of the type specimens 1—5 (see the text) as determined by means of the point counter method. Sukulanrakka, Hirvas, Rovaniemi.

Constituents	1	2	3	4	5
Plagioclase	52.8	24.5	10.6	6.3	10.6
Amphibole	24.6	8.1	8.0	13.8	1.7
Quartz	6.2	39.5	39.6	35.4	58.2
Biotite	2.4	23.5	30.1	6.5	5.2
Epidote	1.1	—	—	—	—
Chlorite	—	3.5	4.0	14.0	22.7
Cordierite	—	—	6.1	22.2	—
Muscovite	—	—	—	—	0.7
Magnetite	12.7	—	—	—	—
Accessories	0.2	0.9	1.6	1.8	0.9
	100.0	100.0	100.0	100.0	100.0

amphiboles. Small grains of epidote are often enlosed by albite. Accessory minerals are sphene and apatite. The texture is evidently subophitic and the recrystallization is weak.

The modal composition of the less altered rock type (specimen 2) is presented in Table 1. In this rock quartz occurs as clear anhedral grains, 0.2—0.8 millimetres in diameter. Plagioclase which is clear and untwinned, displays weak, continuous, normal zoning, and has the composition of oligoclase. The grains are roundish, and are 0.1—0.3 millimetres in diameter. Biotite occurs as reddish brown pleochroic scales, which are 0.2—2 millimetres long. It has been in part altered to the chlorite. Amphibole which occurs as narrow, long, euhedral crystals, 0.2—2 millimetres long, is colorless cummingtonite with $2V\gamma = 71$—$76°$ and $c\wedge\gamma = 19$—$21°$. Scaly aggregates of colorless chlorite with a 2V of nearly $0°$ occur as alteration products of biotite. Accessory minerals are sphene, apatite and ilmenite. The texture is crystalloblastic, with no signs of relict structures.

The modal composition of the third type specimen (3) is presented in Table 1. The quartz is roundish, and 0.1—1.0 millimetres in diameter. Biotite scales, 0.2—3 millimetres long, display strong pleochroic haloes around inclusions of zircon and apatite and have been partly altered to chlorite. Plagioclase is clear and untwinned, with weak normal zoning, and is oligoclase in composition. Its grain size is generally less than 0.1 millimetres. Amphibole occurs as narrow, colorless, euhedral, prisms 0.3—3 millimetres long. They consist of both anthophyllite and cummingtonite with the monoclinic amphibole forming the central part and the orthorhombic amphibole the outer lamellae. The composition face is (100) (see, Eskola, 1914, pp. 183, 193, 199, 206 and 221). In cummingtonite $c\wedge\gamma = 17$—$20°$ and $2V\gamma = 71$—$75°$, and in anthophyllite $2V\gamma = 66$—$69°$. It is obvious that cummingtonite has converted partly into anthophyllite. The chemical compositions of two such amphibole prisms are presented in Table 2. According to these determinations there are no essential differences in the compositions of these amphiboles, cummingtonite and anthophyllite.

TABLE 2

Electron microprobe analyses of two composite amphibole prisms. Anal. J. Siivola.

	Prism 1		Prism 2	
	Cummingtonite	Anthophyllite	Cummingtonite	Anthophyllite
SiO_2	52.4	52.2		
TiO_2	0.15	0.13		
Al_2O_3	2.40	2.20	2.71	2.75
FeO (tot.)	19.0	18.5	15.9	15.1
MnO	0.16	0.16		
MgO	20.1	20.2	18.6	18.7
CaO	0.77	0.26	0.36	0.31
	94.98	93.65		

Cordierite occurs as large euhedral crystals, which enclose grains of amphibole, chlorite, biotite, quartz, ilmenite and feldspar. The cordierite is clear and only faintly pinitized along cracks. Its $2V\alpha = 75$—$82°$. The composition of the cordierite was tested with an electron microprobe analyser. According to two determinations (by J. Siivola) the cordierite contains FeO (tot.) $= 1.96$—1.95 and MgO $= 11.5$—11.8 weight per cent. It is clearly rich in magnesia.

In some cases the cordierite occurs as clear anhedral grains, 0.5—4 millimetres in diameter. Locally the amount of the cordierite may be much greater, as in those rocks containing the large porphyroblasts of the cordierite, and it seems that in such cases especially, the amount of the plagioclase is correspondingly less.

The chlorite of the third type specimen is slightly greenish and is mostly an alteration product of biotite. Small grains of ilmenite, apatite and zircon occur as accessory. — The texture is crystalloblastic.

The modal composition of the fourth type specimen (4) is presented in Table 1. In that rock type quartz occurs as roundish anhedral grains, 0.2—2 millimetres in diameter. Cordierite grains are anhedral, about 0.5—5 millimetres in diameter, and contain numerous small quartz grains as inclusions. The cordierite has $2V\alpha = 78$—$84°$. Amphibole which occurs as euhedral prismatic crystals, 0.2—4 millimetres long, is mainly cummingtonite, with $2V\gamma = 76$—$80°$ and $c \wedge \gamma = 19$—$22°$. In many amphibole prisms the borders are anthophyllite, $2V\gamma = 64$—$77°$. Reddish brown biotite occurs as scales 0.3—2.5 millimetres long, and is partly altered to chlorite. The chlorite grains are almost colorless, and 0.3—1.5 millimetres long. The small, weakly zoned, untwinned grains of plagioclase are about 0.1—1.2 millimetres in diameter. Ilmenite, pyrite, apatite and zircon occur as accessories. The texture is crystalloblastic.

The modal composition of the fifth type specimen (5) is presented in Table 1. In this rock type, quartz grains are roundish, and about 0.1—0.8 millimetres in diameter. The chlorite is faintly greenish in color, and the length of the scales is 0.3—3 millimetres. Its 2V is almost 0°, and it is an alteration product of biotite, cordierite and amphiboles. Plagioclase occurs as very small grains, which are less than 0.2 milli-

TABLE 3

Chemical compositions of the type specimens in weight percentages and weight norms and the Niggli numbers. Analyst P. Ojanperä, trace elements R. Danielsson and V. Hoffren.

	1	2	3	4	5
SiO_2	52.92	64.25	66.97	59.75	65.99
TiO_2	2.01	0.99	0.94	1.33	1.00
Al_2O_3	13.74	11.30	11.21	11.38	11.82
Fe_2O_3	8.42	0.35	0.31	1.22	1.31
FeO	6.58	5.68	6.27	8.18	3.97
MnO	0.07	0.03	0.03	0.04	0.01
MgO	4.27	8.60	8.52	10.62	8.02
CaO	4.40	2.46	1.10	1.27	1.20
Na_2O	6.06	2.24	1.11	1.44	1.70
K_2O	0.28	1.52	1.46	1.06	1.12
P_2O_5	0.16	0.09	0.08	0.10	0.09
CO_2	0.00	0.29	0.00	0.00	0.00
H_2O+	0.88	1.78	1.76	3.10	3.30
H_2O-	0.04	0.06	0.04	0.08	0.12
	99.83	99.64	99.80	99.57	99.65
Rb_2O	0.00	0.006	0.004	0.004	0.004
SrO	0.015	0.007	0.004	0.004	0.004
ZrO_2	0.018	0.014	0.014	0.011	0.013
BaO	0.00	0.04	0.04	0.03	0.03
Cu	0.016	0.002	0.002	0.004	0.001
Ni	0.006	0.007	0.007	0.010	0.007
V	0.040	0.022	0.019	0.028	0.020
Cr	< 0.001	0.015	0.016	0.020	0.016
qu	2.82	23.70	35.67	23.63	35.47
cor	—	1.71	6.00	5.79	5.84
or	1.67	8.96	8.63	6.29	6.62
ab	51.27	18.93	9.38	12.16	14.37
an	9.45	11.65	4.92	5.65	5.40
en	10.63	21.41	21.21	26.44	19.97
fs	1.94	8.56	9.76	11.91	4.56
wo	4.74	—	—	—	—
mt	12.20	0.51	0.44	1.76	1.90
il	3.82	1.88	1.79	2.52	1.90
ap	0.37	0.20	0.20	0.24	0.20
si	142.5	212.2	239.2	177.4	245.3
al	21.8	22.0	23.6	19.9	25.9
fm	49.2	58.9	65.0	70.0	60.5
c	12.7	8.7	4.2	4.0	4.8
alk	16.3	10.4	7.2	6.1	8.8
qz	—22.5	70.2	110.4	53.0	110.1
k	0.03	0.31	0.46	0.33	0.30
mg	0.35	0.72	0.70	0.67	0.74
ti	4.1	2.5	2.5	3.0	2.8
p	0.2	0.1	0.1	0.1	0.1
w	0.54	0.05	0.04	0.12	0.23
c/fm	0.26	0.15	0.06	0.06	0.08
h	7.9	19.6	21.0	30.6	41.0

metres in size. It is weakly zoned and untwinned, and is albite-oligoclase in composition. Reddish brown biotite occurs as small scales and some scaly aggregates contain chlorite, biotite and muscovite. Amphibole occurs scantily, and its grains are ragged

and strongly altered to biotite and chlorite. The muscovite is colorless and occurs mostly together with chlorite and biotite. Ilmenite, sphene, zircon, apatite and tourmaline occur as accessories. Some varieties of this rock type contain no amphibole at all. In such cases the amounts of chlorite and muscovite are greater, and the amount of biotite is smaller.

In all the type rocks described above the textures are rather well preserved, and even the undulatory extinction of quartz is absent or only weak.

CHANGES IN THE CHEMICAL COMPOSITIONS

The chemical compositions of the type specimens are presented in Table 3. Chemical analysis 1 represents a typical metadiabase in the Kemi—Rovaniemi area (see, e.g., Härme, 1949, analyses 1—3 in Table II) although the content of the magnetite of the analyzed rock was somewhat unusually high. In the field this rock type was considered to be the primary metasomatically unchanged rock. The other chemical analyses 2—5, Table 3, represent the compositions of the metasomatically altered rock types. The weight norms and Niggli values have been calculated.

Considering the changes in the total chemical compositions (Table 3; see, Fig. 9) in this metasomatic process some specific features were observed. Starting from analysis 1 (the unaltered metadiabase) in numerical order the amount of SiO_2 increases up to analysis 3 but is somewhat lower in analysis 4 and higher again in analysis 5. The greatest growth in its values is between analyses 1 and 2, i.e., just at the beginning of the metasomatic alteration. The contents of Al_2O_3, CaO, Na_2O and Fe_2O_3 decrease up to analysis 3, and in analyses 4 and 5 their amounts increase slightly. The percentage of MgO rises up to analysis 4 and is lower in analysis 5. The amount of FeO decreases slightly up to analysis 3, then it is higher in analysis 4 and much lower in analysis 5. The amount of K_2O increases up to analysis 3, and in analyses 4 and 5 it lowers somewhat. Notable is also the increase of water especially in analyses 4 and 5.

In spite of the decrease in alumina content, the weight norms of analysis 2 contain *cor* even though that rock type does not yet contain cordierite. This »excess» of alumina is possibly due to the strong decrease of *ab* even though *or* has increased. At the beginning of the metasomatism *an* increases weakly but then it decreases again. The increases of *en* and *fs* are also notable.

The variations of the Niggli values are presented in Fig. 10. The Niggli values are plotted against *si* which forms the abscissa; the numbers of the analyses are shown in parentheses. The lines through the values of analysis 4 are drawn with dotted lines. If we disregard the Niggli values of analysis 4 (see, Fig. 10), we find that the changes in the Niggli values from analysis 1 to 2 and 3 are nearly rectilinear. Thus the first three analyses (1, 2 and 3) already show the direction of the metasomatic alteration. By passing from analysis 3 to analysis 5 the trends of the lines show a reverse tendency. This reveals a change to have taken place during the metasomatic alteration process.
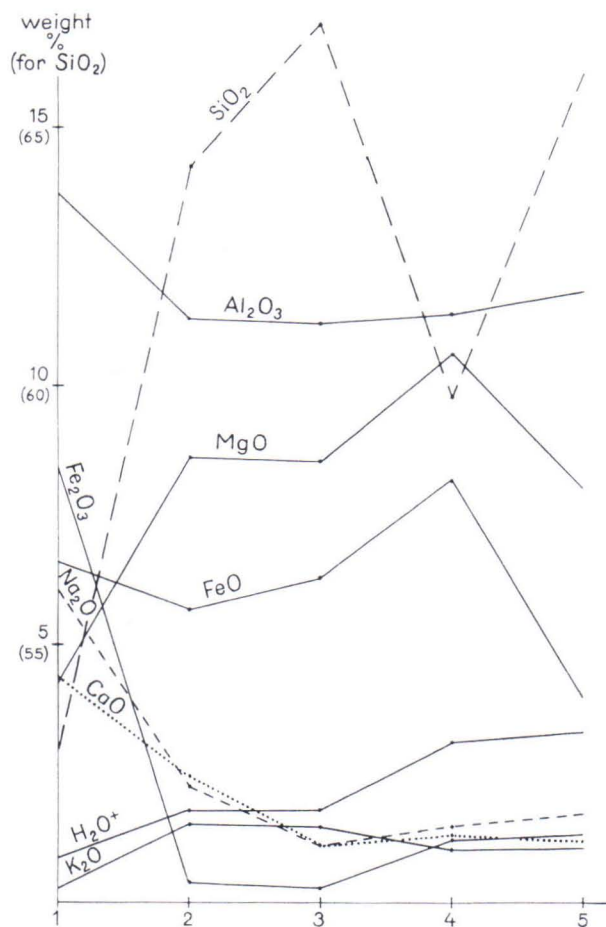
FIG. 9. Variation diagram. The weight percentages of the principal oxides (analyses 1—5) are plotted against the numerical order of the type specimens 1—5 presented in the text. For SiO_2 the ordinate scale is in the parentheses.

However, in comparing analysis 1 with every other analysis it is seen that the changes follow the general tendency of the alteration.

The tendency of the metasomatic alteration during the early stage in thus best revealed by the series of analyses 1, 2 and 3. The tendency seems to be the same during the main phase of the metasomatic process, as well. The chemical composition of type specimen 4 when compared to type specimen 3 deviates from that tendency, but in comparing it to the composition of type specimen 1 (the unaltered rock) the alteration is of the same tendency. Only FeO (see, Fig. 9) makes a deviation, it is notably higher in analysis 4 than in analysis 1. Besides, it should be noted that the value of SiO_2 in analysis 4 (even though it follows the general tendency when
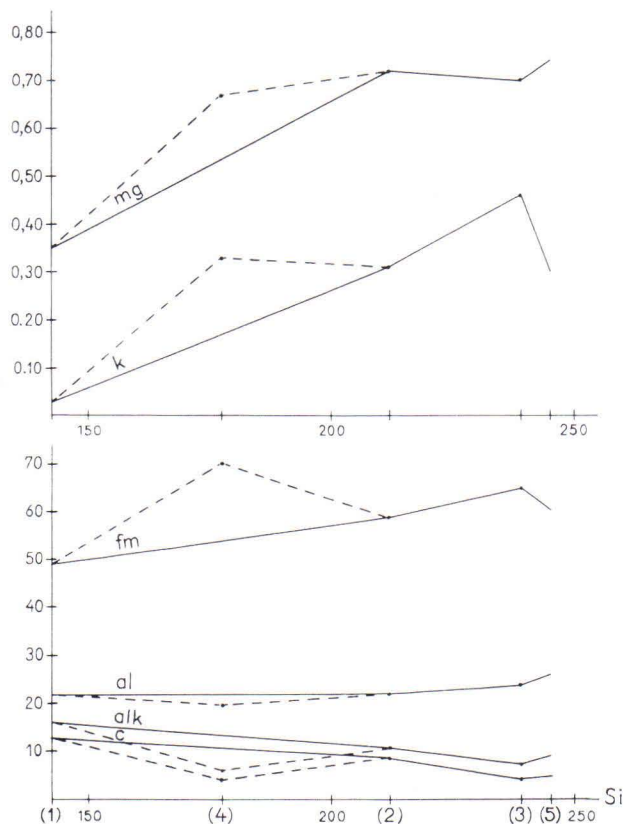
FIG. 10. Variation diagram of the Niggli values. The numerical
order of the analyses is in the parentheses. The solid lines exclude
the values of analysis 3, whereas the broken lines include these
values as well.

compared to its value in analysis 1) is remarkably lower than in analyses 3 and 5. These
facts indicate that the metasomatic alteration has not advanced quite homogeneously,
but that type specimen 4 represents a product of local variation as was already observed
in the field, as well as in petrographic studies.

The compositions of the type specimens are calculated also to the standard cells of
Barth (all calculations are referred to a volume of 160 oxygen anions) in Tables 4.
Each of these formulae represent the compositions of approximately the same volume
unit and thus the metasomatic changes in the compositions are found by subtracting
the formula of the altered (or more altered) rock from that of the unaltered (or less
altered) rock. Since the metasomatic alteration has not been quite coherent, the tend-
ency of the alteration is best revealed by passing from the formula 1 to the formula
2 as well as from 1 to 5. In both compositional changes the same cations have been
added (C makes an exception) and removed. The comparison of the number of

TABLE 4

a. The compositions of the type specimens represented as Standard Cells of Barth (1955).

1. $K_{0.4}Na_{11.2}Ca_{4.4}Mg_{6.0}Fe^{2}_{5.3}Fe^{3}_{6.0}Al_{15.4}Si_{50.2}Ti_{1.5}P_{0.1}C_{0.0}(O_{154.4}OH_{5.6})$
2. $K_{1.8}Na_{3.8}Ca_{2.3}Mg_{11.3}Fe^{2}_{4.2}Fe^{3}_{0.2}Al_{11.8}Si_{56.9}Ti_{0.7}P_{0.1}C_{0.3}(O_{149.4}OH_{10.6})$
3. $K_{1.6}Na_{1.8}Ca_{1.1}Mg_{11.1}Fe^{2}_{4.6}Fe^{3}_{0.2}Al_{11.6}Si_{58.7}Ti_{0.6}P_{0.1}C_{0.0}(O_{149.9}OH_{10.1})$
4. $K_{1.2}Na_{2.4}Ca_{1.2}Mg_{14.1}Fe^{2}_{6.2}Fe^{3}_{0.8}Al_{11.9}Si_{53.2}Ti_{0.9}P_{0.1}C_{0.0}(O_{141.6}OH_{18.4})$
5. $K_{1.2}Na_{2.8}Ca_{1.1}Mg_{10.3}Fe^{2}_{2.8}Fe^{3}_{0.8}Al_{12.0}Si_{56.8}Ti_{0.6}P_{0.1}C_{0.0}(O_{141.0}OH_{19.0})$

b. Changes in the amounts of the cations in the Standard Cells.

By passing	from 1 to 2		2→3		3→4		4→5		1→5	
Ions	+	—	+	—	+	—	+	—	+	—
K	1.4	—	—	0.2	—	0.4	—	—	0.8	—
Na	—	7.4	—	2.0	0.6	—	0.4	—	—	8.4
Ca	—	2.1	—	1.2	0.1	—	—	0.1	—	3.3
Mg	5.3	—	—	0.2	3.0	—	—	3.8	4.3	—
Fe²⁺	—	1.1	0.4	—	—	1.6	—	3.4	—	2.5
Fe³⁺	—	5.8	—	—	—	0.6	—	—	—	5.2
Al	—	3.6	—	0.2	0.3	—	0.1	—	—	3.4
Si	6.7	—	1.8	—	—	5.5	3.6	—	6.6	—
Ti	—	0.8	—	0.1	0.3	—	—	0.3	—	0.9
P	—	—	—	—	—	—	—	—	—	—
C	0.3	—	—	0.3	—	—	—	—	—	—
H	5.0	—	—	0.5	8.3	—	—	0.6	—	13.4
Total of cations	18.7	20.8	2.2	4.7	14.8	5.9	4.7	7.6	25.1	23.7
representing valences	45.0	45.2	8.0	7.7	22.2	22.4	15.7	15.8	49.2	49.4

cations of formula 1 with the numbers of the corresponding cations in formulae 2—5 is illustrated in Fig. 11. In that graph we see that the change in the number of each cation has taken place in the same direction. The only exception is again made by the ferro-ion in the transition from composition 1 to composition 4.

CONCLUSIONS

In the vicinity of Sukulanrakka metadiabase occurs as hypabyssal sills between layers of the sedimentogeneous quartzite. The gradual change of the total composition from a metadiabase into cordierite-anthophyllite-bearing rocks has been very strong. The alteration process must have been metasomatic.

In the vicinity of Sukulanrakka the general strike is rather rectilineal, and so far no field observations show that the metasomatically altered rocks had any special position in a fold. Instead, some altered parts seem to be bordered by faults. The movements have caused also some schistosity. which must be, at least in part, pre- or paracrystalline with regard to the metasomatic alteration. The metasomatizing agents have been acting from beneath. Thus, it appears likely, that the invasion of metasomatizing agents or movements connected with it have also caused the faults and some of the shearing.
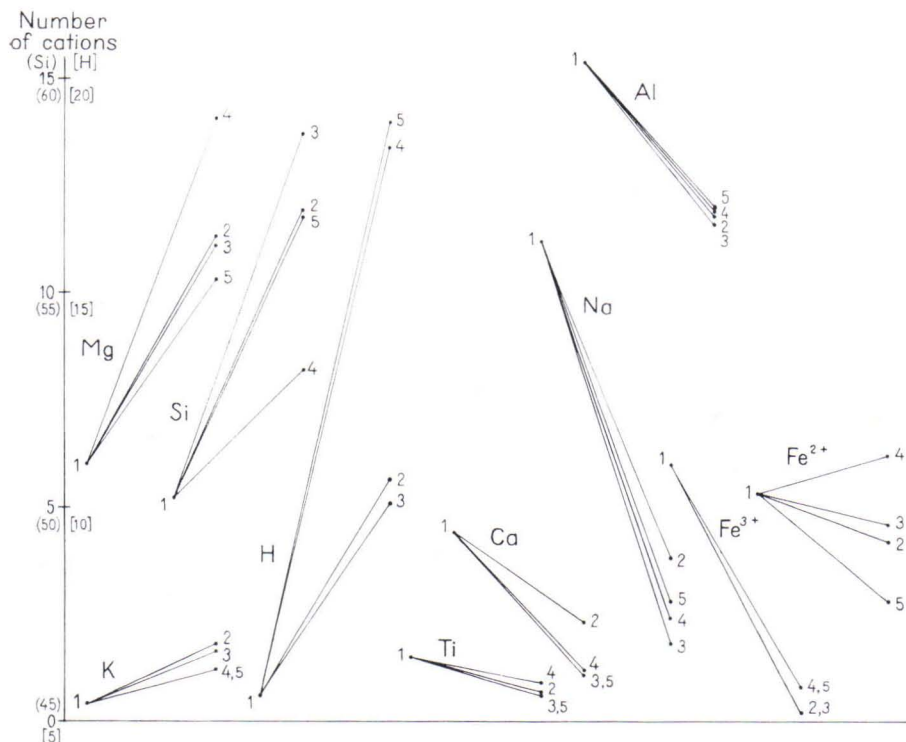
FIG. 11. The amounts of the cations in the standard cell formulae as presented graphically. For Si the ordinate scale is in the parentheses and for H in the brackets. The abscissa is arbitrary. The numbers refer to the formulae and to the type specimens. The deviation from the unchanged rock type (1) is in each figure towards the same direction; the only exception is in the figure for Fe^{2+}.

In the primary rock (metadiabase) plagioclase was albitic whereas in the metasomatically altered rock it has been recrystallized into normally zoned and somewhat more anorthite-bearing plagioclase. The high plagioclase content of the primary rock was strongly decreased in the altered rock, and a new constituent, Mg-rich cordierite, occurs as an important Al-bearing mineral. It is evident that Al-bearing plagioclase of the metadiabase gave rise to the formation of cordierite. In this process Mg and Fe were needed but simultaneously Ca and Na were liberated and removed.

In the primary rock, the amphibole was tremolite-actinolite but during metasomatic alteration it was replaced by cummingtonite, simultaneously with the general removal of CaO. The subsequent conversion of cummingtonite to anthophyllite was caused by a change in P-T-conditions only, without any essential change in chemical composition (see, Table 2).

The metadiabase (1) contains typically only a little biotite but its amount was greatly increased at the beginning of the metasomatism (see, type specimen 2, Table 2). This indicates an essential addition of K_2O. During the course of metasomatism this biotite was altered to chlorite as were also cordierite and the amphiboles.

Type specimen 1 represents the epidote-amphibolite facies, and type specimens 2, 3 and 4 correspond (even if they contain some chlorite as secondary alteration product) to the amphibolite facies, whereas type specimen 5 accords with the greenschist facies. All these facts show that the temperature of this metasomatic process has been, at least at the beginning and during the main phase, rather high. Only during the final stage of the process was the temperature again lower as is shown by the low temperature mineral facies of type specimen 5. Thus a change has taken place during the course of the metasomatic alteration, as indicated by this final retrogressive stage.

Critical inspection of field observations as well as petrographical results help us to interpret the changes in the chemical bulk compositions. During the field study, specimens were megascopically selected (starting from the southern border of the metasomatically altered zone) in numerical order to represent certain stages of increasing metasomatic alteration. As mentioned before, there is in the field no sharp boundary between type specimens 1—3. Some streaky variations occur between rock types 3—5 indicating an inhomogeneity in far-advanced alteration. Type specimen 4 was chosen to represent a more basic variety of alteration. In this respect it is easy to understand the slight compositional deviation of type specimen 4 from the nearly rectilineal trend of the transformation when passing from the rock type 1 to 2 and further into 3. Rock type 5 is then a product of the subsequent alteration stage, and this explains its deflection from the alteration trend of the earlier phase. Thus the general course of the metasomatic alteration is best revealed by the transition from analysis 1 to 2 and 3 and further on to 5.

In the variation diagram (Fig. 9) the weight percentages of the oxides are plotted in the numerical order of the analyses. In this manner of presentation the amounts of most of the oxides of analysis 4 fit well to the general alteration trend. The percentage of SiO makes the greatest deviation, it is more than six percentage units lower than in analyses 3 and 5. Therefore in analysis 4 the percentages of the other oxides are also relatively higher.

Disregarding the Niggli values of analysis 4 in the graph, (Fig. 10) we find interesting regularities:

— the values fm and k increase during the early phase (from 1 to 3) of metasomatism but diminish during the late phase (from 3 to 5);

— the values c and alk diminish in the early phase but increase during the late phase;

— the values of al increases slightly during the early phase and increase even more during the late phase;

— the value of mg (as a matter of fact) increases (and more than fm) during both the early phase and the late phase.

These facts show that the metasomatic process has not proceeded rectilineally but there has been a turning point, a certain kind of culmination, where the concentrations of some acting factors have changed. Most likely this turning point means also a change in physical conditions, especially in the temperature.

The changes in the number of the cations of the Standard Cell formulae are illustrated in Fig. 11. The amounts of the Mg, Si and K cations are lower in formula 5 than in formulae 2 and 3. It could mean that their amounts were decreased during the late phase of metasomatism. The differences are, however, not so great and in part they may also be due to the strong increase in H during the corresponding phase.

The number of the Na, Fe^{3+} and Al cations are somewhat higher in formula 5 than in formula 3 but, considering the inhomogeneity (big porphyroblasts etc.) of type specimens 3 and 5, the differences are not marked enough for any conclusions.

The amount of the Al cation decreases just at the outset of the process (from formula 1 to 2) but after that its amount remains nearly constant. This lowering at the initial stage may, however, be only relative and due to the strong change in the amounts of the other cations at that stage. In many metasomatic processes the Al cation is less mobile to migrate (Härme and Laitala, 1955, p. 98; Härme, 1958, p. 58; Bugge, 1943, p. 139).

As to changes in the amount of Fe^{2+} it is noteworthy that it decreased during the early phase (from formula 1 to 2 and 3) as well as during the late phase (to formula 5), but in formula 4 it is exceptionally high. Many earlier papers dealing with magnesia metasomatism reported an addition of Fe^{2+} together with Mg. The analyses presented here do not show this. However, type specimen 4 was chosen to represent the more basic variety of the alteration products, and perhaps in the future more detailed field studies will prove the more iron-rich alteration products to be rather common. For the time being, the present authors consider type specimen 4 to represent a rather local variety.

Obviously we can conclude that those elements, whose amounts increased notice-ably, especially during the early phase, had relatively high concentrations in the solution which caused the metasomatism. In this sense Si, K, H_2O and Mg are very important. Water and also CO_2 at the beginning of the process, represent the volatiles (see, Härme and Laitala, 1955, p. 98). High amounts of Si and also K are typical of granitizing solutions whereas that of Mg is not. Instead, Mg usually decreases in the granitization.

When considering cations whose amounts diminished we observe that the concen-trations of Ca, Na and Fe (except Fe^{2+} in analysis 4) decreased as in potassium metasomatism (see, e.g., Härme; 1958, p. 52; 1965, p. 21; Härme and Laitala, 1955, p. 97). The Al cation decreased here somewhat as well, but this decrease is not significant. A slight lowering of the Al-content has also, however, been noted in certain cases in potassium metasomatism (Härme, 1955, p. 52).

Summarizing the compositional changes during this metasomatic process we verify that most of them are typical of potassium metasomatism. Exceptions to this are the increase of Mg (at least during the main phase) as well as the exceptional increase of Fe^{2+} and the decrease of Si in type specimen 4.

The enrichment of Mg takes place e.g. during partial anatexis where the restite has been relatively enriched in mafic minerals. In this metasomatic process, however, the

amounts of SiO_2 and K_2O are increased markedly, and that phenomenon is not typical to the restite of partial anatexis. The other possibility for the enrichment of Mg in a metamorphic process is the basic front which is supposed to precede the migmatite front and also the potassium metasomatism. The formation of a basic front is not clear but it is known that the elements Mg, Fe, Ca and very often Na as well, are removed from a granitizing rock. It is still fairly uncertain in which order and to which direction they move. From the elements mentioned the amounts of Ca, Na and mainly Fe have been somewhat diminished here in these metasomatically altered rocks whereas the amount of Mg was increased at least during the early phase. So there is quite near at hand the opinion that the metasomatic alteration of the metadiabase has been caused by granitizing solutions rich in SiO_2 and K_2O. The altered rocks at Hirvas represent products of the beginning of metasomatic alteration in front of the main phase of the granitization (see, Härme, 1965, p. 39) where from one side, the infiltration of H_2O, Si and K, and from another side, the removal of especially Ca, Na and Fe, have begun. These solutions activated the removal of magnesia from a more advanced alteration zone (where the unaltered rock may have been the same meta-diabase), and the magnesia stopped here, and thus here occurred an addition of magnesia.

Taking into consideration the rather strong access of SiO_2 during the whole metasomatic process we can conclude that on the whole no basification has taken place but rather, the alteration was caused by an acid front.

The somewhat opposite direction of the compositional alteration during the final stage of the metasomatism was then obviously due to changes in the concentrations of the acting solutions as well as to changes in physical conditions.

No structural features in the field give sign either of updoming or collapse, and thus it is believed that the metasomatic alteration occurred without changes in volume, i.e., the replacement was ion for ion.

The origin of the hydrous fluids which have caused the metasomatism is not quite clear. As stated before, the character of these fluids is similar to those which in wide areas of Fennoscandia have been the active factor in the formation of potassium-rich migmatites and in potassium-feldspathization and granitization. The Kemi—Rova-niemi synclinorium is on all sides surrounded by the younger migmatitic granite (see, Hackman, 1914, p. 34; Härme, 1949, p. 34) which is a product of potassium meta-somatism. Even if the nearest known occurrence of this granite is at a distance of about ten kilometres from the Sukulanrakka hills the many features of the metasomatism at Hirvas bear witness to the action of the same potassium-rich migmatizing agents. In this case the area of the metasomatically altered rocks at Hirvas may be situated on a migmatite aureole.

CORRELATIONS AND DISCUSSION

Eskola (1914) in his classical study of the Orijärvi aureole concludes upon the metasomatism at Orijärvi as follows (p. 262): ». . . the rocks of the Orijärvi aureole owe their peculiar characters to pneumatolytic agencies which have caused considerable changes in their composition. These changes have, for the greatest part, consisted in a metasomatic replacement of lime, soda and potash by iron oxides and magnesia» . . . »In some localities the alteration consisted in a considerable enrichment in silica». On the agents which caused the process he stated (*op.cit.*, p. 259): »Iron-, magnesia- and silica-bearing vapors or solutions soaked into the leptites round the granite mass and caused a thorough alteration in their mineral and chemical composition . .», and further (p. 260):» . . . the pneumatolytic metamorphism was caused by the oligoclase granite . . .»

The differences between the metasomatism in Orijärvi area and at Hirvas are the different behaviours of iron and potassium. At Orijärvi the amount of iron mainly increased during the process whereas at Hirvas its amount was decreased (except in type specimen 4). At Orijärvi potassium was, in general, removed, but at Hirvas the amount of the potassium was increased. Only when speaking about the andalusite-bearing quartz-mica rock Eskola remarked (*op.cit.*, p. 257): »At certain points an addition of considerable amounts of potash is probable.» The removal of lime and soda as well as the addition of magnesia are the main common features. In addition, there are many other similarities in both areas.

At Orijärvi metasomatic alteration has not taken place quite uniformly in one direction, but in some cases an element has been enriched and in other cases it has been removed. It is important, however, to note that the primary rock was not homogeneous but contained both mafic and felsic rocks. This being the case, it seems likely that the possible addition or removal of any element must depend on the compositions of the adjoining rocks, i.e. on the chemical potentials during the prevailing physical conditions.

Tilley (1935; *cf.* Tilley and Flett, 1930) has described a metasomatic process which took place in greenstones in Cornwall. This process has many similarities with that at Hirvas. In Cornwall the primary rock was a greenstone which prior to metasomatic processes had been subject to shearing and dynamic metamorphism so that banded rock types are common. Different varieties of hornfelses are products of this metasomatism. Tilley has verified that in these altered rocks anthophyllite may appear together with cummingtonite but it usually becomes prominent only when cordierite is developed. Homoaxial growth of anthophyllite and cummingtonite are also found, where the core of the prism is usually cummingtonite (Tilley and Flett, 1930, p. 29). The cordierite is a product of replacement after plagioclase. The anthophyllite-cordierite hornfelses contain also biotite and sometimes quartz.

In Cornwall as well, the alteration has not been quite coherent and homogeneous, but local variations occur. Tilley (1935, p. 194) has assumed that the metasomatic

processes have operated without volume change. Hot solutions emanating from a granite source have passed through the greenstones, and (*op.cit.*, p. 202)» . . . the metasomatic processes involved a widespred removal of lime, accession of silica, alkalis, particularly potash, and an *internal* magnesia metasomatism as contrasted with an accession of magnesia from an external source which characterizes the Orijärvi and Falun regions».

Reynolds (1947, p. 35) has criticized the study of Tilley and has suspected the magmatic origin of the greenstones. Mainly on the basis of chemical compositions she concluded that the greenstones were originally a calcareous sedimentary series with intercalations of igneous rocks of spilitic type. She (*op.cit.*, p. 42) agreed, however, that certain hornfelses cannot be matched by either igneous or normal sedimentary types but that they have undergone a radical chemical change after which they have been markedly enriched at least in Fe. »The additional enrichment of the cummingtonite-anthophyllite rock series in Mg is probably, as Tilley suggested, the result of an internal migration of Mg». (Reynolds, 1947, p. 43.)

When discussing the metasomatic processes in Central Sweden Sundius (1935) believed the magnesia to have enriched, even if in small amounts, in residual solutions of granite magma. Magnusson (1940, p. 100) regarded metasomatic processes to have been caused by solutions which have been driven in front of intruding granite.

In his interesting paper of the Kongsberg-Bamble formation Bugge (1943) dealt with the formation of cordierite-anthophyllite rocks. In these rocks (Bugge, 1943, p. 97) the content of magnesia is very high whereas that of iron is relatively low. The amount of potassium is small but that of water is rather large. However, there are different cordierite-anthophyllite (or gedrite)-bearing varieties which show a variation in the amounts of e.g. quartz, micas and plagioclase. Bugge (1943, p. 92) proved the cordierite to have been formed metasomatically after plagioclase. He stated that through the addition of magnesia to the more basic hornblende-plagioclase rocks, anthophyllite will generally be formed first, and, when all the hornblende has disappeared, cordierite. The cordierite-anthophyllite rocks contain also quartz and biotite.

Bugge considered the cordierite-anthophyllite rocks to be products of contact metasomatism caused by solutions (ichor) which contained both juvenile and palingenic magmatic material. The composition of the ichor corresponded to that of diluted granitic solutions. The magnesia was leached from gabbros and amphibolites in connection with an advancing of disperse solutions during migmatization.

Bugge (*op.cit.*, p. 143) has concluded that the metasomatism took place during the migmatization period, and that the metasomatism often had a different character in rocks of different composition. »The silicate rocks show a distinct selective filter-action, and which of the constituents in the liquid system (the ichor) that will be fixed, depends upon the chemical and mineralogical composition of the silicate rock, as well as the P-T conditions» (Bugge, 1943, p. 143).

There are many occurrences of cordierite- and anthophyllite- or cummingtonite-bearing rocks in the Precambrian of Fennoscandia (e.g., Väyrynen, 1928, p. 118;

Härme, 1949, p. 20; Lundegårdh, 1968, p. 335; Rouhunkoski, 1968, p. 104) but unfortunately only few of them have been investigated in more detail.

Simonen (1948, p. 38) has described an occurrence of cummingtonite-, anthophyllite- and cordierite-bearing rocks near the town Hämeenlinna in southern Finland. He considered those to be products of metasomatism in which a decrease in CaO, Na_2O and K_2O as well as an increase in FeO- and MgO-contents have taken place. The strongest altered rock is an anthophyllite-cordierite rock which contains quartz but no plagioclase. Simonen (*op.cit.*, p. 44) has stated that the mobilization of magnesia has been caused by the intrusion of synkinematic rocks, and is older than the crystallization of the synkinematic granodiorites.

In all the cases described above the occurrence of sulphides is common and their emplacement is evidently connected with metasomatic processes. This is also the case at Hirvas even though, so far, sulphides have been found only in small amounts. The introduction of the sulphides is also proof of migration.

Even though in the examples cited above, there are some differences in which elements have been introduced and which have been removed, there are still, however, some common features. An example is the increase of MgO and the decrease of CaO. Many researchers have also linked metasomatism to granites and/or granitic solutions. Most likely the differences between areas of metasomatism depend on the primary compositions of the acting fluids and of the host rocks as well as on the physical conditions prevailing in the different zones of metasomatism (*cf.* Bugge, 1943, p. 143; Mehnert, 1968, pp. 333—335). In each case the chemical potentials are determined by those factors.

Korzhinskii (1968, p. 223) has stressed that generally in metasomatism the action of the infiltrated solution forced by a gradient of pressure is more significant than that of the diffusion. In the present case of magnesia metasomatism the question is still open but it seems that the injected solutions have acted forcefully.

Not long ago Grant (1968, p. 927) discussed the origin of cordierite-anthophyllite-bearing rocks, and he concluded that they may be formed from various common protoliths through partial melting, filter pressing, and recrystallization. This is quite possible, but no signs of any melt formed in the alteration process has been found in the field either at Hirvas or at Orijärvi. Most of the investigators have presented the opinion that the alteration process has taken place without volume change which would be expected in the residuum after a partial melting.

Schreyer and Yoder (1964, p. 332—334) have shown that Mg-cordierite is a relatively low-pressure mineral, and the formation of cordierite in the presence of excess water vapor needs moderate to relatively high temperatures, 450°—700°C (about 490°C at 1 kb). Hirschberg and Winkler (1968, p. 17) have shown the breakdown of chlorite (where the ratio $Fe^{2+}/Fe^{2+} + Mg$ varied in the experiments from 0.4 to 0.8) and the formation of cordierite in the presence of biotite to have taken place at $513 \pm 10°C/1$ kb.

Hinrichsen (1967, p. 17) has determined the lowest stability limit of anthophyllite (Mg/Mg + Fe- ratio 0.4) to be about $520 \pm 10°C$/ 1 kb. Schürman (1967, p. 274) has presented the stability limit of cummingtonite (MgO/FeO + MgO-ratio 0.5; in addition about 2 weight % CaO) to be about 550°C/ 1 kb. Choudhuri (1970, p. 926) has compiled a tentative P-T-x-diagram as a rough model for the coexistence of the amphibole pairs. According to it the stability field of the pair anthophyllite-cummingtonite lies in the temperature range of about 580°—700°C/ 1 kb. These temperature values are quite near to those given by Engel and Engel (1958, p. 1372) who studied the progressive metamorphism and granitization of paragneiss in northwest Adirondack Mountains. They have reported the »degranitization» or »basification» of the gneiss to have been a metamorphic process that began at about 550°C and was well defined at 600°C.

Many features of the metasomatism at Hirvas point out that the beginning and the main phase of the process have taken place within the same range of the experimental temperatures as cited above whereas the last phase took place at a remarkably lower temperature range where cordierite and amphiboles were no longer stable under hydrous conditions. On the other hand, from the study of the type specimens it seems that the conversion of tremolite to cummingtonite has antedated the formation of cordierite. This could mean that the temperature was highest just at the beginning of the metasomatic process. This problem, however, requires further study.
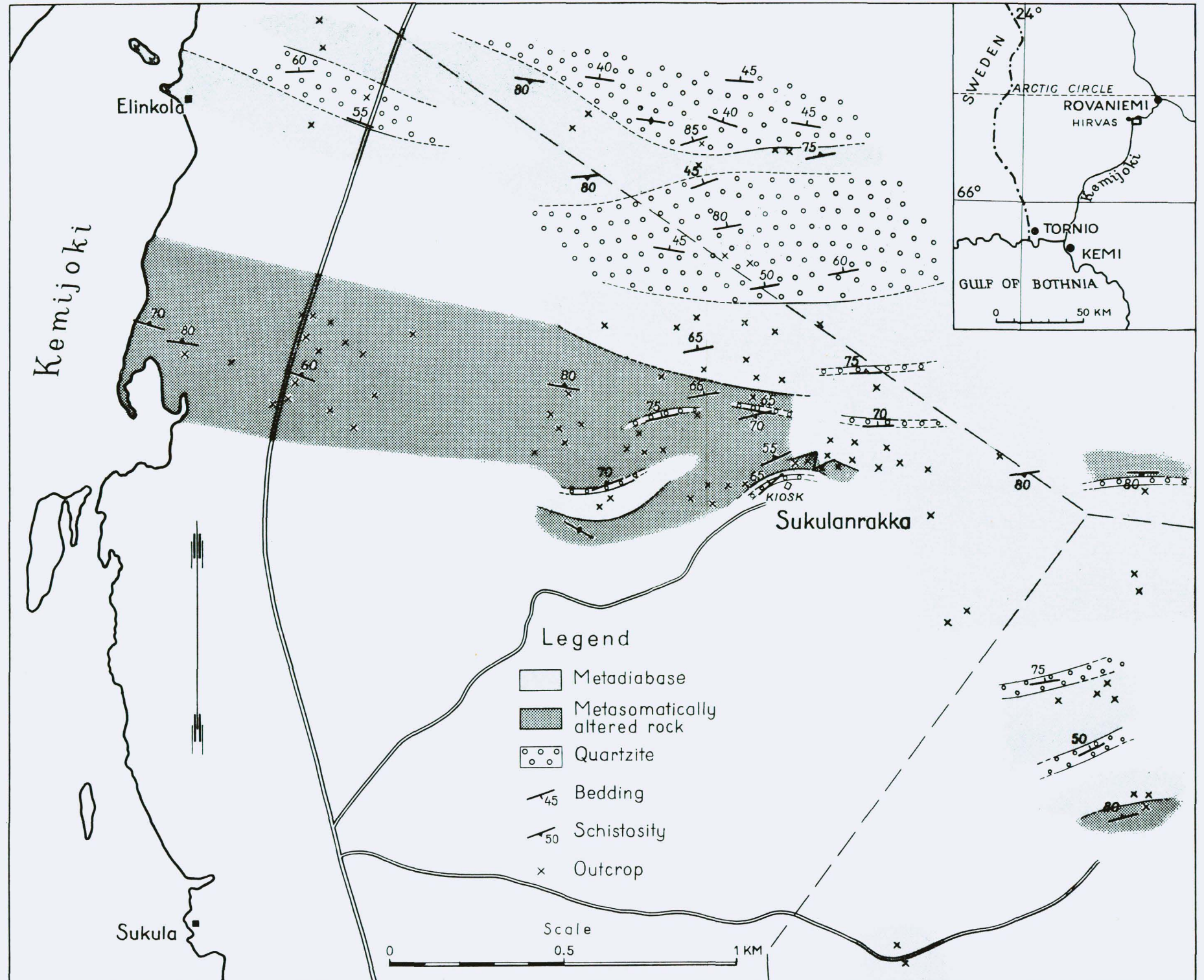
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ACKNOWLEDGMENTS

Outline geological map of
Sukulanrakka area
Hirvas, Rovaniemi

Kemijoki

Elinkola

Sukula

Sukulanrakka

KIOSK

Legend

Metadiabase

Metasomatically altered rock

Quartzite

Bedding

Schistosity

Outcrop

Scale

0   0.5   1 KM

SWEDEN

ARCTIC CIRCLE

ROVANIEMI

HIRVAS

TORNIO

KEMI

Kemijoki

GULF OF BOTHNIA

0   50 KM

24°

66°