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On the petrochemistry of rapakivi granites with special reference to the Laitila massif, southwestern Finland

by Atso Vorma

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ON THE PETROCHEMISTRY OF RAPAKIVI GRANITES WITH SPECIAL REFERENCE TO THE LAITILA MASSIF, SOUTHWESTERN FINLAND

BY

ATSO VORMA

WITH 42 FIGURES, 12 TABLES, 4 APPENDICES AND ONE PLATE

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Rapakivi is defined in a way that restores to the term the sense given it by Sederholm at the end of last century.

The chemical characteristics of different occurrences of rapakivi in the Baltic Shield are compared in the light of the Niggli and Harker variation diagrams as well as normative *Qu-Or-Ab* triangular diagrams. The comparison reveals, among other things, that the largest of the massifs, the Wiborg massif, is the most basic and richest in calcium. Also the differentiation of the magma in this massif is different from that in other massifs.

The petrochemistry of different varieties in the Laitila massif is described in detail, and 35 new silicate analyses are presented. The composition of the massif and its differentiation are discussed in the light of both the major elements analyzed and certain trace elements, such as F, Li, Rb, Ba, Sr, Zr, Hf, Th, U and REE. The average composition of the Laitila rapakivi is compared with that of granites in general. The comparison reveals that the Laitila rapakivi is richer in K, F, Li, Rb, Zr, Hf, REE, Th and U, and poorer in Ti, Al, Fe, Mn, Mg, Na, P and Sr than granitic rocks in general, and, in addition, that it has exceedingly low Mg/Fe and K/Rb ratios and a high Ca/Sr ratio.

A model for the origin of rapakivi magma is proposed. The production of the magma is interpreted as an orogenic process and its emplacement as a postorogenic process. The generation of the rapakivi magma is attributed to ultrametamorphism under the conditions of intermediate- to high-pressure granulite facies. Under dry conditions, the hydrated minerals, hornblende, biotite and muscovite, melt incongruently and yield, besides the formation of a granitic melt, which is undersaturated in respect of water, a refractory residue of aluminium silicates (sillimanite, garnet, cordierite), pyroxenes and magnetite leading to the rocks of the granulite facies. During the compressional stage of the orogeny, the granitic magma remains as a pore fluid in the lower crust. During the distensional postorogenic stage, the magma collects to form larger magma chambers and the gravimetric diapiric rise upwards takes place.

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INTRODUCTION

This thesis aims to clarify differences in chemical composition between various rapakivi granite massifs in the central and eastern parts of the Baltic Shield. It also gives a detailed description of the chemical characteristics of different rapakivi granite varieties occurring in the Laitila massif, in southwestern Finland. The mode of generation of the rapakivi magma is the last topic to be dealt with.

Because the word has been used in too wide a sense in geological literature, the author thinks it appropriate to define rapakivi as a geological term.

In Finnish, rapakivi means crumbly stone or crumbly rock. The name is mentioned as early as 1694 by Urban Hjärne (Eskola 1930 a and b). Common to the rocks called rapakivi is their marked tendency to crumble, this property being the most conspicuous in granites possessing the rapakivi texture, to be defined in the following. In geological literature, the term »rapakivi texture» was established by Sederholm in 1891.

Rapakivi texture *sensu stricto*, viz., as it occurs in the classic rapakivi granites of the Baltic Shield, is characterized by

- — the ovoidal shape of alkali feldspar insets, 3—4 cm and more in diameter,
- — mantling of the ovoids by oligoclase-andesine shells, 1—3 mm in thickness, some ovoids, however, remaining unmantled,
- — the ubiquitous occurrence of two generations of alkali feldspar and quartz, the idiomorphic older generation of quartz having been crystallized as high quartz.

When the content of mantled ovoids in the rock exceeds that of unmantled ones, the typical rapakivi texture or wiborgitic texture (wiborgitic ovoid = mantled ovoid) results. When the unmantled ovoids prevail over the mantled ones, the rapakivi texture is called pyterlitic (pyterlitic ovoid = unmantled ovoid). Both wiborgitic and pyterlitic ovoids contain so-called concave quartz inclusions, often also quartz and biotite inclusions in concentric rings. In wiborgitic ovoids, the repetition of mantling occurs frequently. For descriptions of different kinds of ovoids and details about the rapakivi texture, see, for example, Vorma 1971, pp. 22—30.

Rapakivi texture *sensu lato* involves only the presence of mantled alkali feldspar ovoids.

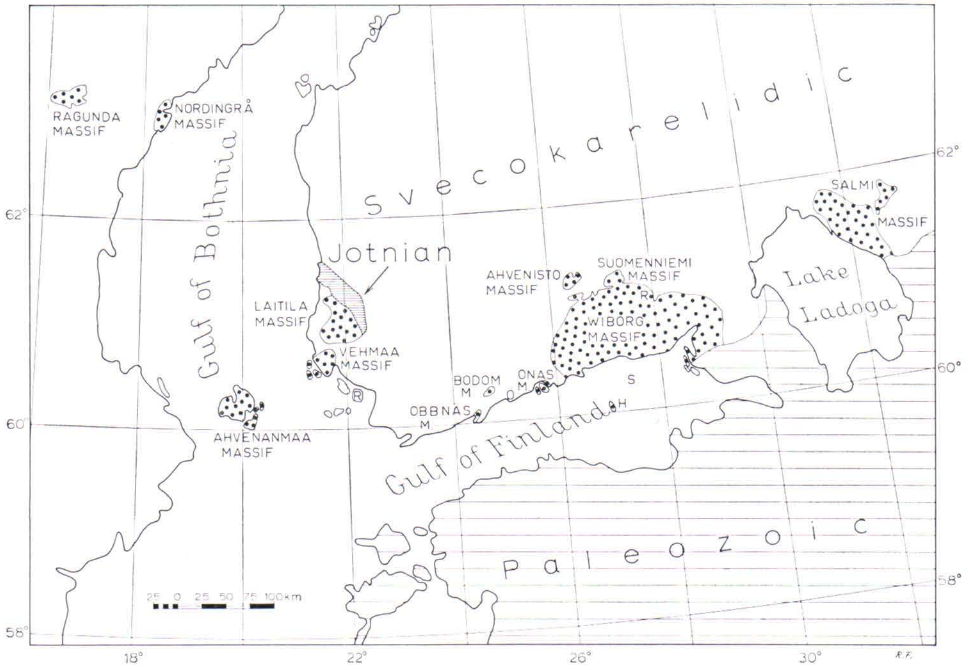


Fig. 1. The occurrences of rapakivitic rocks in the Baltic Shield. H, Hogland (Suursaari); S, Someri; R, Ruoholampi; Ö, Östersundom; R, Ruissalo; M, massif (for Onas, Bodom and Obbnäs).

The rapakivi texture has been encountered especially in granites belonging to a definite group of Precambrian granites, especially in the Baltic Shield (see Fig. 1), but also, e.g., in the Ukrainian Shield. These epizonal disharmonious granites — rapakivi granites *sensu stricto* — are Subjotnian (Hoglandian) in age (ca. 1700 m.y.), postorogenic in respect of the Svecokarelidic orogeny. The largest of the massifs, the Wiborg massif in Finland, extends into the USSR and covers an area of 18,000 sq. km. About 80 per cent of the massif is composed of rapakivi granites having the typical rapakivi texture (wiborgite, i.e., typical rapakivi granite). This grades over to varieties in which the pyterlitic texture prevails (pyterlite), also to porphyritic rapakivi granite in which unmantled angular and subangular alkali feldspar phenocrysts prevail, and to even-grained granites, still called rapakivi even though the rapakivi texture is lacking. Also granite porphyry with a well-developed rapakivi texture is frequently met with in the Wiborg rapakivi area.

Other well-known rapakivi areas in the Baltic Shield (Fig. 1) include those of Laitila, Vehmaa, Ahvenanmaa (Åland), etc. in Finland, and Ragunda, Nordingrå, etc. in Sweden, and Salmi in Soviet Karelia. In the Ukrainian Shield, the Korsun—Novomirgorod and Korosten massifs are the best known. Also in southern Greenland, granites of this group of rapakivi granites *sensu stricto* have been encountered.

Rapakivi granites *sensu lato* comprise both anorogenic and orogenic granites of different ages. The only criterion on the basis of which they have been called rapakivi is the occurrence of the mantled alkali feldspar ovoids in them. These granites often occur as contact facies of nonrapakivitic acid plutonic rocks.

The foregoing definition of rapakivi restricts the term rapakivi granite *sensu stricto* to the Subjotnian rapakivi granites. In the present paper, the term rapakivi is used in this sense only, i.e., in the same sense given it by Sederholm back in 1891. Later, the term rapakivi became vaguer. The foregoing definition distinguishes the terms rapakivi texture and rapakivi granites and also emphasizes the need to distinguish rapakivi granites *sensu stricto* (rapakivi granites proper) from rapakivi granites *sensu lato*. The author thinks it unfortunate that the rocks grouped under rapakivi granites *sensu lato* have, on the whole, been designated as »rapakivi.»

Altogether, the present paper is confined to the rapakivi granites *sensu stricto* occurring in the central and eastern part of the Baltic Shield, i.e., in southern Finland and Soviet Karelia.

A HISTORICAL APPROACH

Main features of rapakivi composition

In addition to its formational and textural aspects, the term rapakivi implies a third aspect, a compositional one.

At the end of the nineteenth century, the chemical characteristics of rapakivi granites were still quite vaguely understood (Sederholm 1891). At the beginning of the 20th century, it was only Hackman's (1905) collection of analyses of Finnish rocks that gave the main characteristics of the chemical composition of rapakivi granites.

In Paul Niggli's great work »Gesteins- und Mineralprovinzen» (1923), the rapakivitic magma type was established. As Niggli values will be used in the present work, it is appropriate to cite the main characteristics of Niggli's rapakivitic magma type. He distinquished three different magma series, viz., »Kalk-Alkalireihe», »Natronreihe» and »Kalireihe.» In his potassic series, he arranged many magma groups; the rapakivitic magma type belongs to the granitosyenitic magma group. The rapakivitic magma type is characterized, according to Niggli, by the following Niggli values: *si*, 380; *al*, 40; *fm*, 18; *c*, 9; *alk*, 33; *k*, 0,50; and *mg*, 0,27. Besides rapakivi granites *sensu stricto*, Niggli included in this magma type many two-mica granites, quartz porphyries, porphyries, trachytes, quartz trachytes, etc. In addition, some of the rapakivi granites were included by Niggli in the adamellitic magma type of the granitosyenitic magma group. At this point, note should be taken of the two Niggli values, $k = 0.50$ and $mg = 0.27$, both characterizing the two important features of rapakivi composion: a magma rich in K_2O and low in MgO. Both of these figures will be refined for rapakivi granites *sensu stricto*. In 1936 Niggli increased the number

Table 1.
The »average«[1]) composition of rapakivi granites arrived at by different workers and the rapakivitic magma type of Niggli

	Sederholm's »average« (N = 9) (1925 a)	Sahama's »average« (N = 37) (1945)	Sahama's standard mixture (1945)	Rapakivitic magma type of Niggli	
				(1923)	(1936)
SiO_2	72.57	71.79	72.58		
TiO_2	0.25	0.52	0.34		
Al_2O_3	12.62	12.95	12.98		
Fe_2O_3	1.45	0.99	0.86		
FeO	2.41	2.77	1.83		
MnO	0.02	0.05	0.11		
MgO	0.46	0.28	0.25		
CaO	1.34	1.59	1.01		
Na_2O	2.30	2.83	3.01		
K_2O	6.10	5.48	5.28		
P_2O_5	0.02	0.13	0.18		
H_2O+	0.49	0.54	0.66		
H_2O-		0.12	0.38		
F	—	0.23	0.36		
BaO	—	0.08	0.10		
ZrO_2	—	0.06	0.12		
	100.03	100.41	100.05		
—O = F	—	0.10	0.15		
	100.03	100.31	99.90		
si	388	375	408	380	350
al	40	40	43	40	41
fm	20	18	15	18	18
c	8	9	6	9	9
alk	32	33	36	33	32
k	0.64	0.56	0.54	0.50	0.45
mg	0.17	0.12	0.10 [2])	0.27	0.3
c/fm	0.40	0.50	0.40 [3])	0.50	0.50

[1]) Actually the mean of the existing analyses.
[2]) Should be 0.14.
[3]) Should be 0.42.

N = number of analyses included.

The Niggli values of first three columns from Sahama, 1945.

of magma types considerably. He now placed the rapakivitic magma type in the leucosyenite-granitic magma group of the potassic magma series. Niggli's »new» rapakivitic magma type was characterized by $si = 350$, $al = 41$, $fm = 18$, $c = 9$, $alk = 32$, $k = 0.45$ and $mg = 0.3$.

In 1925, two papers worth citing were published in which the composition of rapakivi was dealt with. Sederholm calculated the »average» (Table 1) of all the existing rapakivi analyses in connection with his study on the average composition of the earth's crust in Finland, and Wahl produced an extensive description of the Wiborg massif, accompanied by a study of the chemistry of the massif. Characteristic features of rapakivi emphasized were the high contents of K_2O and SiO_2 and low contents of MgO, Al_2O_3 and CaO. As a whole, the rapakivi massifs were regarded as quite homogeneous. Two years later, in 1927, Eskola examined the rapakivis in the light of Niggli values. In 1928, Eskola emphasized the role of fluorine in the composition of rapakivi.

In 1945, Sahama published his extensive thesis on the chemistry of eastern Fennoscandian rapakivi granites. His aim was to determine the special features of these rocks in relation to other granitic rocks. Sahama's main concern was to give a picture of the average rapakivi composition, without considering the differences between different rapakivi massifs and different rapakivi varieties, and to shed light on the significance of trace elements in the rock. For this purpose, Sahama collected all the reliable rapakivi analyses (37) available at that time, and calculated their averages (actually means) and Niggli values (Table 1). Sahama also prepared a so-called standard mixture of rapakivi granites by choosing a number (54) of samples from all the rapakivi areas he was investigating (the Ahvenanmaa, Vehmaa, Laitila, Wiborg and Salmi massifs). This mixture was chemically analyzed for some 50 elements. The main elements and certain trace elements from Sahama's study are listed in Table 1.

Concerning the »average» chemical composition of rapakivis in relation to other granitic rocks, Sahama stated (op.cit., p. 39) that rapakivis contain somewhat less Al_2O_3, MgO and CaO than granites on the average, the alkali ratio, in addition, being clearly altered in favour of potassium. It is easily seen (Table 1) that Sederholm's »average», based on 9 analyses, is quite similar to Sahama's »average», based on 37 analyses, and that Sahama's standard mixture, concerning certain elements (see also Niggli values), deviates from the two first mentioned. As the present author sees it, this deviation is partly due to the sampling for the standard mixture. By far the largest of the massifs, the Wiborg massif, is represented in the standard mixture only by 8 samples, of which no more than possibly one is of wiborgite rapakivi, the rapakivi variety that prevails in the Wiborg massif. About 80 % of the Finnish part of the massif is of wiborgite (Simonen and Vorma 1969, p. 6). All the other samples are of rapakivi varieties having a comparatively limited occurrence. This sampling method evidently causes the FeO and CaO figures in Sahama's standard mixture to be considerably lower than in the averages referred to.

In regard to the trace elements, Sahama stated that especially enriched in the rapakivi granites of Fennoscandia are F (0.36 %), ZrO_2 (0.12 %), HfO_2 (0.0028 %), BaO (0.10 %), Rb_2O (0.16 %) and PbO (0.006 %), that comparatively enriched are Ta_2O_5 (0.0001 %) and REE (about 0.03 %) and that rapakivi granites show a great paucity of Li_2O (0.0050 %) and Cs_2O (less than 0.001 %). Some of these figures will be worked out more precisely in the present paper.

Certain characteristic features of rapakivi as compared with other granitic rocks have recently been studied by Velikoslavinskiy (1973). He demonstrated that the Dala granites and Dala porphyries and Rätan granite in Sweden as well as certain subplatform granites in Kola Peninsula — all about the same age as rapakivi granites *sensu stricto*, and, lika the Kola granites, designated as rapakivi — can be distinguished from rapakivis *sensu stricto* by the different fields these granites occupy in the variation diagrams of K/Na + K plotted against Fe'' + Fe''' + Mn/Mg + Fe'' + Fe''' + Mn, K/Na + K against SiO_2, and Fe'' + Fe''' + Mn/Mg + Fe'' + Fe''' + Mn against SiO_2, respectively.

Inhomogeneities inside and between different massifs

As soon as more and more analyses of different rapakivi varieties accumulated, it became clear that there is quite a large compositional range of rapakivis, even though the prevailing varieties showed a highly homogeneous composition. Wahl (1925) distinguished in the Wiborg massif two magma types, a pyterlitic one and a wiborgitic one. The pyterlitic type was characterized by a considerably higher SiO_2 content than the wiborgitic; the wiborgitic type was, on the contrary, richer in CaO, Na_2O, Al_2O_3 and Fe_2O_3 (total iron). The characteristic Niggli values of both of these magma types are given in Table 2. It is particularly noteworthy that Wahl gave to the terms pyterlitic and wiborgitic rapakivi not only a textural but also a chemical meaning.

Hackman (1934) in his study of the different rapakivi varieties and their composition in the Lappeenranta area, in the northeastern part of the Wiborg massif, did not quite accept Wahls's idea of separate pyterlite and wiborgite magmas and, like Sederholm in 1891, wrote (Hackman 1934, p. 44): ». . . dass das Wiborger Rapakiwi Massiv im Ganzen eine grosse Homogenität aufweist.» In spite of this homogeneity, Hackman demonstrated, further, that locally the rapakivi massif is highly differentiated. Hackman presented a large number of chemical analyses of different varieties (op.cit.).

Sahama (1945, p. 38) also suggested that Wahl's wiborgite and pyterlite should be used in a textural sense only, thus ruling out the compositional aspect altogether. Sahama pointed out that Wahl's pyterlite and wiborgite compositions are by no means characteristic of those types alone, but that rocks of the same composition are met with even among rapakivis texturally not at all representing these types. Further, according to Sahama, the types of composition mentioned by no means represent any specially abundant occurrences, but only certain members of a continuous series.

It is now clear that each rapakivi massif is in fact a composite pluton, built up of many intrusive phases differing to some extent in composition. Also the intrusive phases themselves were more or less differentiated. Further, a considerable time gap between the emplacement of different intrusive phases is demonstrated. Velikoslavinskiy (1953) and Vorma (1971) have discussed the intrusive phases of the Wiborg massif, Sviridenko (1968) those of the Salmi massif, Savolahti (1956) those of the Ahvenisto massif, and Kanerva (1928) those of the Vehmaa massif.

Table 2.
Niggli values for the pyterlite and wiborgite magma types of Wahl (1925, p. 81)

	si	*al*	*fm*	*c*	*alk*	*k*	*mg*	*c/fm*	*qz*
Pyterlite magma.	470	40	17	7	35	0.62	0.15	0.48	220
Wiborgite magma.	340	40	17	11	32	0.54	0.15	0.68	120

As for each rapakivi massif taken separately, the characteristic features of the chemical composition of the different rapakivi varieties are known quite well. With respect to the Salmi massif, see Sviridenko (1968); the Wiborg massif, see Wahl (1925), Hackman (1934), Velikoslavinskiy (1953), and Vorma (1971); the Ahvenisto massif, see Savolahti (1956); and Vehmaa massif, see Kanerva (1928). The rapakivi from the Laitila massif is represented only by a few scattered analyses, the Ahvenanmaa massif by two. The same is true of the Suomenniemi, Onas, Obbnäs, and Bodom massifs. The Kokemäki granite, which was regarded by Sederholm as belonging to his third group of granites, i.e., as being older than rapakivi granites proper, is considered by the present author to belong genetically together with the Laitila massif, from which it is separated by a rift now filled by Jotnian sandstone.

Up till now, there has been no serious attempt to examine the differences in chemical composition between different massifs. Wahl (1925, p. 99), it is true, wrote: »Wenn man die verschiedenen fennoskandischen Rapakiwigebiete mit einander vergleicht, so zeigt es sich, dass die Gesteine der östlichsten Gebiete, des Pitkäranta- und des Wiborger Gebietes, die kalireichsten sind. Je westlicher das Gebiet liegt, um so mehr scheint das Verhältnis zwischen den Alkalien in den Magmen sich zu Gunsten des Natrons verschoben zu haben. Freilich sind die analysierten Gesteine von Åland (nur eine Analyse) und des Haupttypus von Rödön etwas zersetzt (wohl pneumatolytisch) und der Kaligehalt dieser Analysen ist vielleicht auch deshalb ein niedrigerer. Das noch westlicher gelegene Vorkommen von Ragunda bildet aber schon einen Übergang zu den Magmen der Natronreihe, und gelegentlich kommen in manchen Abarten der Ragunda-Gesteine sogar die für die Natronreihe charakteristischen Alkaliamphibole vor. Hierdurch bilden die Ragunda-Gesteine petrographisch gewissermassen einen Übergang zwischen den eigentlichen Rapakiwigebieten des östlichen und mittleren Fennoskandiens und den Graniten mit Rapakiwistruktur bei Drammen, die sich den Natrongesteinen des Kristianiafeldes anschliessen. Entsprechend dieser Zwischenstellung des Ragundaer Stammagmas sind auch die intermediären Gesteine des Ragunda-Gebietes, die Augitsyenite, den Monzoniten nahe verwandt.»

A study of the systematic differences between different rapakivi massifs in the central and eastern parts of Fennoscandia is one of the main tasks of the present work.

RAPAKIVI GRANITES OF EASTERN FENNOSCANDIA

Massifs

A comparison of different massifs calls for a short characterization of them first. The massifs treated here are shown in Fig. 1. The Onas, Obbnäs, Bodom and Kokemäki granites, which were regarded by Sederholm (1925 b) as nonrapakivitic and older than the rapakivi granites proper, have been grouped in the present paper among the rapakivis because of their rapakivitic age and composition. The characterization will begin with the largest of the massifs, viz., the Wiborg massif.

The *Wiborg massif* (ca. 18,000 sq.km) is a composite pluton composed of at least four, possibly more intrusive phases (Vorma 1971). For the distribution of different rock types in the Wiborg massif, see the petrological map quadrangles, on a scale of 1: 100 000, compiled by Laitakari and Simonen (1962), Simonen and Lehijärvi (1963), Laitala (1964), Lehijärvi (1964), Vorma (1964), Simonen (1965, 1973 and 1975), Simonen and Tyrväinen (1965), Meriläinen (1966), Lehijärvi and Tyrväinen (1969), and Simonen and Laitala (1970 and 1972). The rock types distinguished here are briefly characterized, after Simonen and Vorma (1969), as:

Wiborgite (Fig. 2), which shows a typical rapakivi texture, is the most abundant rock type of the rapakivi area. It is a coarse-grained porphyritic granite with ovoids of orthoclase surrounded by plagioclase mantles. The mantled ovoids are densely distributed. The main minerals are alkali feldspar, plagioclase and quartz. Hornblende and biotite are the typical mafic silicates, and the alteration products are iddingsite and chlorite.

The dark-coloured wiborgite has a sparse content of alkali feldspar ovoids, which are mantled by plagioclase. In addition, this variety contains dark-coloured, zoned plagioclase as porphyritic grains. The main minerals of the dark-coloured wiborgite are the same as in the normal wiborgite, but in addition it contains olivine, iddingsite and grunerite. Furthermore, the plagioclase and hornblende contents are higher than those in normal wiborgite.

The pyterlite is a coarse-grained porphyritic granite with ovoids of alkali feldspar, but around the ovoids there are either no mantles of plagioclase or only very sporadic occurrences of them. The contents of alkali feldspar and quartz are higher and that of plagioclase lower than in normal wiborgite. The most characteristic Fe-Mg silicate is biotite, whose alteration product is chlorite. Hornblende is usually lacking.

The porphyritic rapakivi granite is characterized by an abundance of angular porphyritic grains of alkali feldspar without mantles of plagioclase. The mineralogical as well as chemical composition of this variety is quite similar to that of the pyterlite.

The dark-coloured rapakivi granite is texturally an even-grained rock of medium or coarse composition. Some varieties contain, however, large ovaids of alkali feldspar. The green colour of the rock is due to the weed texture produced by the green hornblende. This green-coloured rapakivi variety has been called tirilite (cf.,

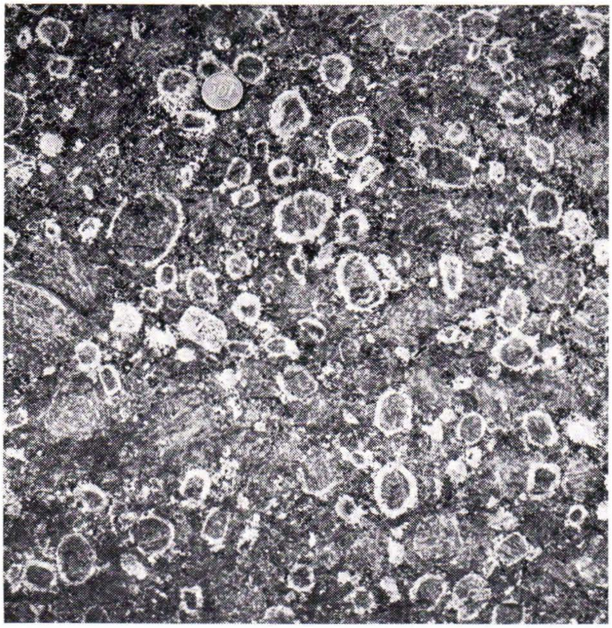


Fig. 2. Wiborgite of the Wiborg massif. Summa, Hamina. The plagioclase-mantled wiborgitic ovoids are clearly in view, the unmantled, pyterlitic ones, poorly so. 1/5.0 natural size. Photo: Atso Vorma.

Hackman 1934). It contains abundant quartz, plagioclase and alkali feldspar in highly variable proportions, and hornblende, biotite, and fayalite are the mafic silicates. Hornblende is always present and in greater amounts than biotite. The alteration products of the afore-mentioned Fe-Mg silicates are iddingsite, grunerite and chlorite. The mineralogical and chemical composition of the dark-coloured rapakivi is related to that of the dark-coloured wiborgite.

The even-grained biotite rapakivi granite is medium- or coarse-grained, potassium-rich granite. Usually red, it sometimes also has a greyish tint. The main minerals are alkali feldspar, quartz and plagioclase. Biotite, altered partly into chlorite, is the main mafic mineral. Hornblende occurs only sporadically. The mineralogical as well as chemical composition of the even-grained rapakivi granite is similar to that of the pyterlite.

The even-grained hornblende rapakivi texturally resembles even-grained biotite granite. The main minerals are the same as in biotite rapakivi; the hornblende, however, prevails over the biotite. In chemical composition, the rock approaches or is identical to wiborgite rapakivi.

The porphyry aplite is a rare rapakivi variety that contains sparsely distributed, mantled or unmantled ovoids of alkali feldspar in a fine-grained aplite-granitic matrix.

Table 3.
Distribution of the different rapakivi varieties in the Finnish part of the Wiborg rapakivi massif, after Simonen and Vorma 1969

Rock type	Per cent (of area)
Wiborgite	76.2
Dark-coloured wiborgite	4.9
Pyterlite	6.1
Porphyritic rapakivi granite	1.2
Dark-coloured rapakivi granite	3.1
Even-grained rapakivi granites	7.8
Porphyry aplite	0.7
Quartz porphyry and granite porphyry	< 0.1
Aplite and pegmatite	< 0.1

The mineralogical and chemical composition of the porphyry aplite is similar to that of the pyterlite and even-grained biotite rapakivi.

Dikes of quartz porphyry and granite porphyry cut the principal rapakivi varieties and the migmatitic country rocks of the rapakivi massif. The mineralogical and chemical composition of these rocks is similar to that of the even-grained biotite rapakivi.

The aplites and pegmatites, which cut the principal rapakivi types, are both mineralogically and chemically related to the even-grained rapakivi granite.

The distribution of rock types in the Finnish part of the Wiborg rapakivi massif is presented in Table 3 (Simonen and Vorma 1969).

Vorma (1971) divided these petrographic varieties into several intrusive phases. The first intrusive phase is represented by e.g., tirilite (a fayalite-bearing ferrohastingsite granite) — Lappee granite (an even-grained ferrohastingsite granite) — Sinkko granite (a porphyritic biotite granite, more basic than the pyterlitic magma of Wahl) in the surroundings of Lappeenranta, in the northeastern part of the massif. The second intrusive phase is represented by the major rapakivi granites: dark and darkish-coloured wiborgite — normal wiborgite — hornblende rapakivi — pyterlite/porphyritic rapakivi — biotite rapakivi/porphyry aplite — dike rocks. The Ca-rich members of this series are characterized by a rapakivi texture. This intrusive phase is composed of several subphases the emplacement of which followed one after another so rapidly that no cooling down and chilling could take place before the next magma was ejected; consequently, it has not been possible to distinguish these subphases from each other. The third intrusive phase is represented by granite-porphyritic masses at the margin of the Wiborg massif. In this phase has been included, e.g., the Jaala-Iitti »dike,» which is over 20 km in length and from a few hundred meters to three km in breadth. Here the petrographic varieties (see Lehijärvi and Lonka 1964) range from tirilite to hornblende rapakivi (a granite porphyry with a rapakivi texture) and even-grained biotite rapakivi. In the last intrusive phase been included the quartz porphyry dikes that were chilled against the rocks of the second intrusive phase and that also cut the country rocks of the rapakivis.

For a more detailed description of the varieties and their mutual relations, the reader is referred to the works of Wahl (1925), Hackman (1934), Velikoslavinskiy (1953) and Vorma (1971).

In close connection with the Wiborg massif are the volcanic equivalents of rapakivi, viz., *the quartz porphyry of Hogland* and *Someri* (Wahl 1947) in the Gulf of Finland and *the porphyries in the roof pendants near Lappeenranta* (Vorma 1975).

The *Suomenniemi massif* (365 sq.km) is composed of an older coarse-grained, hornblende-bearing biotite rapakivi without the typical rapakivi texture. A younger hornblende rapakivi, which is finer in grain than the major variety mentioned, covers an area of some 40 sq.km. Granite porphyry and quartz porphyry dikes cut the massif. For more detailed descriptions of this multiphase pluton, see Pipping (1956) and Simonen and Tyrväinen (1965).

The *Ahvenisto massif* (242 sq.km), also called Mäntyharju massif, is composed of a central coarse-grained biotite rapakivi and a younger medium-grained hornblende rapakivi. The rapakivi texture is lacking in both of these two major varieties. As dike rocks porphyry aplite, quartz porphyry and pegmatite are encountered. For a detailed description, the reader is referred to Savolahti (1956) and Lehijärvi and Tyrväinen (1969).

The *Onas massif* (270 sq.km) is composed of a coarse-grained hornblende-bearing biotite granite. No rapakivi texture is encountered. For further details, see Borgström (1931) and Laitala (1964 and 1965).

The *Bodom massif* (ca. 80 sq.km) is composed of a medium-grained hornblende-biotite granite and a coarse-porphyritic biotite granite, the mutual age relations of which are unresolved. In addition, it contains a granodioritic variety older than the hornblende-biotite granite. The massif is cut, moreover, by different kinds of granitic dikes. For further details, see Sederholm (1926), Halonen (1954) and Härme (1969).

The *Obbnäs massif* (ca. 70 sq.km) is composed largely of a coarse-porphyritic biotite granite, with a hornblende-biotite granite occuring in places. Also medium-grained varieties are met with. For further details, the reader is referred to Sederholm (1926) and Laitala (1960 and 1961).

The *Salmi massif* (> 3,000 sq.km) in Soviet Karelia is, like the Wiborg massif, a composite pluton, built up of wiborgite, even-grained biotite granite, pyterlite, »uneven-grained» granite, granite porphyry, and quartz porphyry. The wiborgite texture is not well developed. When it does occur, the plagioclase mantles are thin and sparse. For details, see Sahama (1945) and Sviridenko (1968).

The *Laitila massif* (ca. 1,400 sq.km) in southwestern Finland is a composite pluton, too, where most of the varieties met with in the Wiborg massif are encountered except that the wiborgite proper is only very seldom met with. The normal rapakivi of Laitila is the prevailing variety; texturally pyterlite, it falls in chemical composition between the wiborgite and the pyterlite of the Wiborg massif. This normal Laitila rapakivi grades over and is penetrated by other rapakivi varieties, of which a detailed description will be given on pp. 37—56.

The *Vehmaa massif* (ca. 700 sq.km) is composed mainly of rapakivi identical with the normal rapakivi of the Laitila massif. It is penetrated by younger varieties of the rock, viz., pyterlitic, even-grained and porphyry-aplitic varieties. For details about this composite pluton, see Kanerva (1928).

The *Åland massif* (ca. 4,000 sq.km, according to Hausen (1964), when the submerged portions are taken into account). The prevailing variety is the »typical Åland rapakivi.» It contains wiborgitic ovoids, which are, however, quite small, 1—2 cm in diameter. Aplite granite and granophyre are also met with. No up-to-date petrographic description of different varieties is available.

Apart from the main Åland massif is the small *pyterlite body of Kökar.*

Gulf of Bothnia. The granophyres and quartz porphyries from the bottom of the Gulf of Bothnia, found as erratic boulders in southwestern Finland, are also regarded as rapakivitic in origin. For details, see Eskola (1928, 1934 and 1963).

Quartz porphyry dikes. Many of the rapakivi massifs referred to are associated with swarms of rapakivitic quartz porphyry dikes. They are associated, e.g., with the Ahvenisto massif (Savolahti 1956), Suomenniemi massif (Pipping 1956, Simonen and Tyrväinen 1965), Wiborg massif (Vorma 1971), Salmi massif (Sviridenko 1968) and Laitila massif (Haapala and Ojanperä 1972). In addition, there are dikes or swarms of dikes whose connection to any specific massif is questionable. Thus, along the coastal area, between the southeastern and southwestern Finnish rapakivi massifs, quartz porphyry dikes have been encountered, measuring individually up to several meters in thickness. The dikes have been described, e.g., from Östersundom (Borgström 1907 and 1947 and Saastamoinen 1956), where there exists a swarm of dikes, from Degerby, Inkoo (Laitala 1960 and 1961) and from Ruissalo, Turku (Pehrman 1941).

In many of the rapakivi areas mentioned, basic Subjotnian rocks have been found. They range from olivine- and quartz diabases to plagioclase porphyrites, and from gabbro-anorthosite to anorthosite. They are of the same age as rapakivi. Their genetic relation to rapakivi granites has been the subject of much discussion. On the whole, these rocks will be omitted from the following discussion of the chemical composition of rapakivis.

Chemical characteristics of the various occurrences of rapakivitic rocks

Analytic material used for this study

The number of chemical analyses (totalling 225) included in the present study, their distribution between the different occurrences of rapakivitic rocks and the sources of the analyses are given in Table 4. As shown, the largest of the massifs, the Wiborg massif, is represented by 37 chemical rock analyses. The Salmi massif is the most thoroughly investigated, judging, at least, by the number of rock analyses, which in the present study amounts to 83. The Laitila massif, from which till now only a few rock analyses have been done, is represented here by 52 of them, most of them being new. The bulk of the discussion in the following is concerned with these three massifs, Laitila, Wiborg and Salmi. All the other massifs are represented by only a few analyses. In relation to the size of the massif, the Åland massif is very poorly represented by the chemical analyses, the Ahvenisto massif very well.

Variation diagrams

The chemical data on each occurrence of rapakivitic rock will be given in the form of Harker diagrams (the Laitila, Wiborg and Salmi massifs), in the form of Niggli variation diagrams (all the occurrences) and in the form of contoured triangular

Table 4.

Number of chemical analyses included in the present study, their distribution between different occurrences of rapakivitic rocks and the source of the analyses. The table also serves as a guide in studying the Harker and Niggli variation diagrams, Figures 3—7

Occurrence of rapakivitic rocks	Number of analyses included (225)	Range of SiO_2 (wt. %)	Range of *si* (Niggli value)	Analyses from
Wiborg massif	(37)			Hackman 1905, Wahl 1925, Hackman 1934, Wahl 1938, Sahama 1945, Simonen and Vorma 1969, Vorma 1971, and Haapala 1974
Dark and darkish wiborgite	4	64.7—69.4	266—330	
Wiborgite	4	68.9—71.5	308—343	
Pyterlite	5	75.1—77.7	446—518	
Porphyritic rapakivi normal type	2	75.1—76.2	467—489	
Sinkko granite	1	70.7	357	
Dark and darkish even-grained rapakivi (incl. tirilite), fayalite-bearing	8	61.1—69.9	215—341	
Even-grained hornblende rapakivi, reddish brown	4	67.1—68.1	285—313	
Even-grained biotite rapakivi	5	73.4—74.9	411—458	
Porphyry aplite	1	74.4	445	
Granite porphyry	1	74.7	445	
Quartz-monzonite porph.	1	64.2	260	
Quartz porphyry	1	70.9	382	
Ruoholampi roof pendant in Wiborg massif	(7)			Vorma 1975
Felsite	1	67.8	316	
Felsite porphyry	4	66.4—71.1	291—361	
Quartz porphyry (Hiidenniemi porphyry)	2	69.6—70.0	351—360	
Hogland (Suursaari) and Someri lava flows	(13)			Lemberg 1867 and Wahl 1947
Quartz porphyries	13	62.8—74.6	256—459	
Suomenniemi massif	(1)			Vorma 1971
Hornblende-bearing biotite rapakivi	1	74.4	443	

(Table 4, contd)

Occurrence of rapakivitic rocks	Number of analyses included (225)	Range of SiO_2 (wt. %)	Range of *si* (Niggli value)	Analyses from
Ahvenisto massif	(10)			Savolahti 1956 and three unpublished analyses
Hornblende rapakivi	4	65.9—69.5	267—326	
Biotite rapakivi	4	71.6—76.7	384—489	
Porphyry aplite	1	73.4	413	
Quartz porphyry	1	77.5	507	
Onas massif	(2)			Hackman 1905 and Borgström 1931
Biotite granite	2	71.1—73.8	356—424	
Bodom massif	(3)			Halonen 1954 and an unpublished analysis from Prof. M. Härme, Geological Survey of Finland
Even-grained granite	2	71.0—74.3	368—424	
Porphyritic granite	1	73.4	423	
Obbnäs massif	(2)			Sederholm 1926 and Lokka 1934
Coarse-porphyritic (?) granite	2	68.4—72.3	310—393	
Salmi massif	(83)			Sviridenko 1968
Wiborgite	27	66.8—74.0	302—420	
Even-grained biotite rapakivi	13	72.9—76.7	406—510	
Pyterlite	7	72.6—76.1	415—481	
Uneven-grained biotite rapakivi	23	68.4—76.5	324—495	
Coarse-ovoidic granite with a fine-grained groundmass (granite porphyry)	9	71.9—75.8	377—480	
Aplite	4	71.6—76.2	371—458	
Laitila massif	(52)			The present paper, Appendix 2
See Appendix 1.		See Fig. 29	See Fig. 30	
Vehmaa massif	(6)			Kanerva 1928
Normal Vehmaa rapakivi	3	68.0—71.4	311—366	
Even-grained rapakivi	2	71.5—74.1	375—433	
Porphyry aplite	1	71.9	387	
Åland (Ahvenanmaa) massif	(2)			Sederholm 1934
Normal Åland rapakivi	1	70.6	335	
Quartz porphyry	1	77.4	519	
Gulf of Bothnia	(5)			Eskola 1928 and 1934
Quartz porphyry	2	72.0—72.5	389—398	
Felsite porphyry	2	72.3—73.4	403—411	
Graphic granite	1	74.5	451	
Östersundom dike swarm	(1)			Borgström 1907
Quartz porphyry	1	66.7	291	
Ruissalo dike	(1)			Pehrman 1941
Quartz porphyry	1	69.3	354	

diagrams (the Laitila, Wiborg and Salmi massifs) showing the distribution of normative *Qu-Or-Ab*. In the diagrams, the different occurrences of rapakivitic rocks are kept separate, though the different rock types are not indicated. As regards the Harker and Niggli variation diagrams, the approximate location of each rock type can be found on the diagrams with the aid of Table 4, where the range of SiO_2 (Harker diagram) and *si* (Niggli diagram) is given for each rock type. As for the Laitila massif, a detailed description of it is given in Appendices 1—3.

Harker variation diagrams

The data from the Laitila, Wiborg and Salmi massifs are given in Fig. 3 in the customary way. In the diagrams, Al_2O_3, $FeO_{tot.}$, K_2O, Na_2O, CaO, MgO, TiO_2 and MnO are plotted against SiO_2. Different kinds of best fit curves were calculated to make the comparison between the three massifs easier. It turned out that concerning Al_2O_3, K_2O and Na_2O against SiO_2, the parabolic regression proved of best value, and concerning $FeO_{tot.}$, CaO, MgO, TiO_2 and MnO against SiO_2, the exponential regression was the best one. The parabolic regression fitted the analytic points to an equation of the form $Y = a + bX + cX^2$ by the method of least squares, the exponential regression fitted the points to an exponential curve of the form $Y = ab^X$. In addition to the constants *a*, *b* and *c*, the correlation coefficients (*r*) and the standard error of estimate (S_{YXX^2} and S_{YX}) were calculated. For the interested reader, these figures are given in Table 5.

Table 5.

Regression constants (*a*, *b*, and *c*), correlation coefficients (*r*), standard error of estimate (S_{YXX^2} and S_{YX}), and the number of chemical analyses (N) included in the regression analyses in which the curves with the best fit in Harker diagrams were determined

Laitila massif

			Parabolic regression			
	a	*b*	*c*	*r*	S_{YXX^2}	N
Al_2O_3 ...	—127.75	4.2177	—0.0313	0.7408	0.6963	52
K_2O	—101.30	3.0059	—0.0211	0.3028	0.6495	»
Na_2O	—37.33	1.1278	—0.0079	0.1654	0.4787	»
			Exponential regression			
	a	*b*		*r*	S_{YXX^2}	
$FeO_{tot.}$ ..	41 301	0.8749		—0.7013	0.1552	52
CaO	1 574	0.9046		—0.7024	0.1161	»
MgO	11.56	0.7783		—0.4301	0.6011	»
TiO_2	17 047	0.8594		—0.5582	0.2592	51
MnO	401.8	0.8787		—0.6867	0.1546	»

(Table 5, contd)

Wiborg massif

Parabolic regression

	a	b	c	r	s_{YXX^2}	N
Al_2O_3	28.618	—0.1489	—0.00098	0.8417	0.8212	37
K_2O	—34.488	1.0824	—0.00732	0.3369	0.7962	»
Na_2O	—47.617	1.4771	—0.01077	0.4343	0.5204	»

Exponential regression

	a	b	r	s_{YXX^2}	N
$FeO_{tot.}$	3 008.9	0.9095	—0.8395	0.1175	37
CaO	3 616.8	0.8972	—0.8941	0.1040	»
MgO	1 504.9	0.8867	—0.6568	0.2662	36
TiO_2	2 557.5	0.8853	—0.8231	0.1679	33
MnO	152.9	0.8909	—0.7423	0.1992	31

Salmi massif

Parabolic regression

	a	b	c	r	s_{YXX^2}	N
Al_2O_3	—6.276	0.8111	—0.00749	0.7078	0.7220	83
K_2O	—37.385	1.3543	—0.0105	0.6340	0.5508	»
Na_2O	30.109	—0.7859	0.00565	0.1922	0.4198	»

Exponential regression

	a	b	r	s_{YXX^2}	N
$FeO_{tot.}$	2 389.3	0.9133	—0.7311	0.0980	83
CaO	1 109	0.9069	—0.6889	0.1191	»
MgO	14 107	0.8591	—0.5542	0.2614	79
TiO_2	6 609	0.8664	—0.5537	0.2497	83
MnO	38.69	0.9087	—0.4812	0.2075	69

The regression curves for the three massifs are superimposed in Fig. 4. These facilitate the comparison of the three Harker diagrams of Fig. 3. The conclusions that can be drawn from the study of Figs. 3 and 4 are briefly:

- The largest of the massifs, the Wiborg massif, is considerably richer in CaO, slightly richer in TiO_2 and somewhat poorer in Al_2O_3 than the smaller Laitila and Salmi massifs.
- The Wiborg massif is more differentiated than the other two massifs. This can be seen owing to
  1. the compositional range of the Wiborg massif is larger than that of the other massifs
  2. a possible gap in the compositional range of the Wiborg massif. Very many of the analyses show an SiO_2 concentration between 65 and 70 per cent, very few between 70 and 75, but again very many around 75 per cent. In

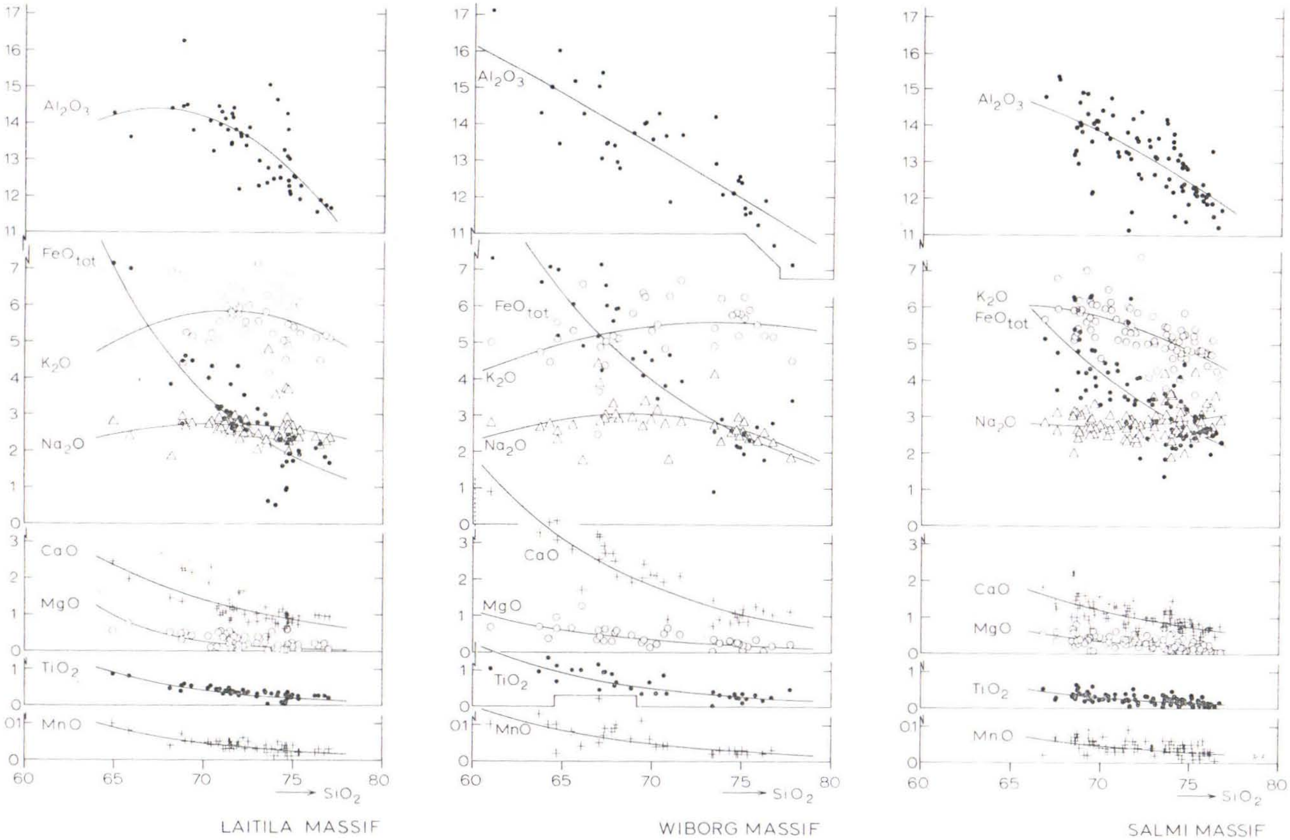


Fig. 3. Harker diagrams of the rapakivi granites contained in the Laitila, Wiborg and Salmi massifs.

the diagrams of the Laitila and Salmi massifs, no such gap can be found. In the Wiborg massif, the compositional range of 65—70 per cent SiO_2 corresponds to Wahl's wiborgite magma, the compositions around 75 per cent SiO_2 to Wahl's pyterlite magma! In the case of the Laitila and Salmi massifs, most of the analytic points lie between 70 and 75 per cent SiO_2, i.e., corresponding to the compositional gap of the Wiborg massif.

— The differentiation has a different course in the massifs. This can be seen in the study of the K_2O and Na_2O curves. In the Wiborg massif, the K_2O seems to increase with increasing SiO_2. In the Laitila massif, the picture is not so clear. In the case of the Salmi massif, there is a marked decrease of K_2O with increasing SiO_2. The slight increase in Na_2O with increasing SiO_2 is observable in the Salmi massif while in the Laitila and Wiborg massifs these elements seem to have a slight negative correlation.

— The curves representing $FeO_{tot.}$ and MgO also show differences. As regards the Wiborg and Salmi massifs, the respective curves are quite similar. As for the Laitila massif, at low SiO_2 values both of these curves register higher values than those of the Wiborg and Salmi massifs, but with increasing SiO_2 the curves drawn from the Laitila massif fall much steeper than those from the other two massifs. This means that in the Laitila massif, iron and magnesium are more highly concentrated in the more basic rapakivi varieties than in the Wiborg and Salmi massifs.

Niggli variation diagrams

From most of the chemical analyses referred to in Table 4, Niggli values were computed. Only a few of the analyses were disregarded because of their incompleteness in regard to some elements — MgO and FeO, e.g., were not determined. That the analyses might stand comparison, only the standard elements of the silicate analyses were included. Thus, e.g., Li_2O, Rb_2O, SrO and BaO were excluded even though these oxides had been analyzed.

The Niggli *si*, *k*, *mg*, *al*, *fm*, *alk* and *c* values are presented in the six diagrams of Figs. 5 and 6. Fig. 5 gives the Niggli values of rocks from the Laitila, Wiborg and Salmi massifs. In Fig. 6, the diagrams are composite; i.e., in the same diagram, the Niggli values of rocks of more than one occurrence of rapakivitic rocks are given. Each occurrence has its own symbols, as indicated in the diagrams. All the data obtained from rocks in southwestern Finland, excluding those of the Laitila massif, are given in the diagram on the left side; the data from southeastern Finland, excluding the data from the Wiborg massif, in the diagram on the right; and the data from the volcanic/subvolcanic rapakivitic rocks of the Wiborg massif in the middle diagram.

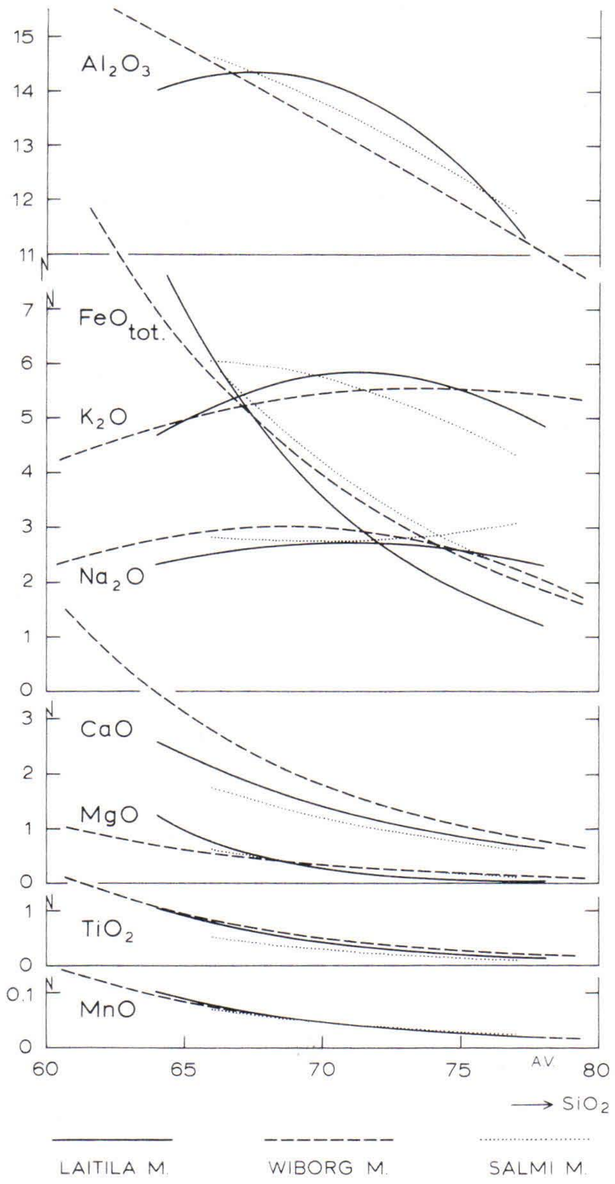


Fig. 4. The regression curves of Fig. 3 superimposed for a comparison of the Harker diagrams of the Laitila, Wiborg and Salmi massifs.

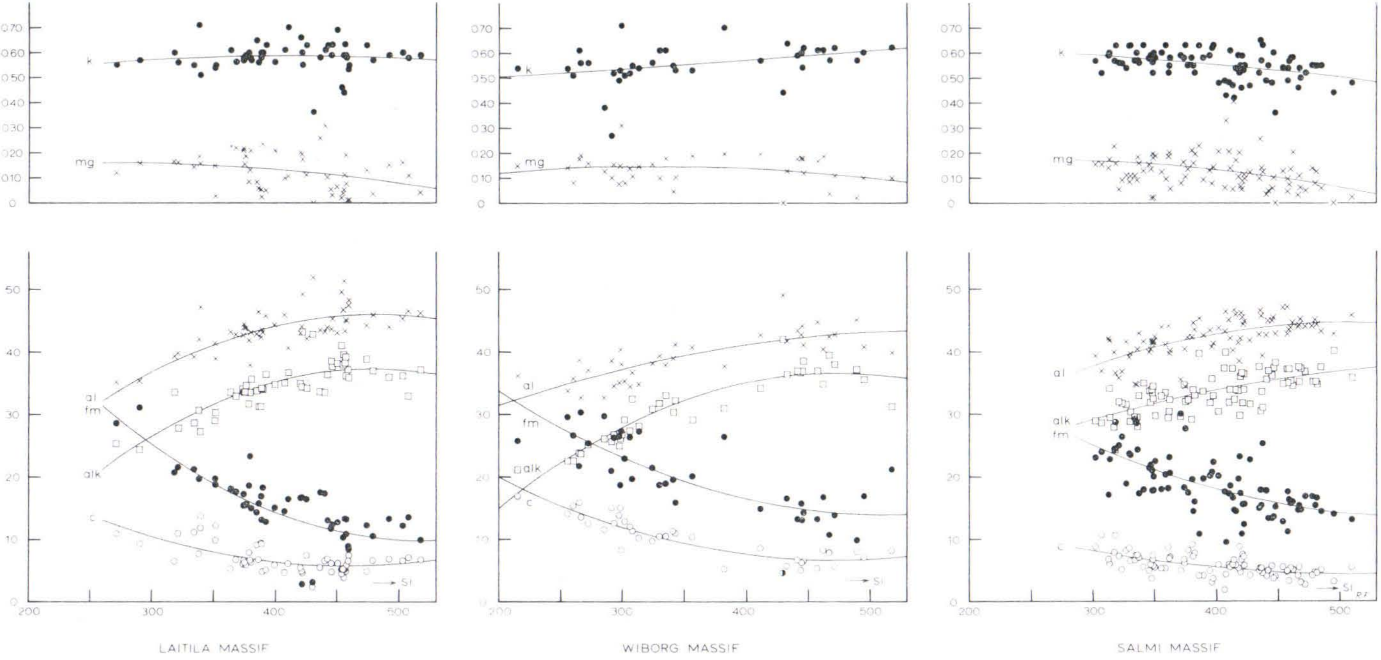


Fig. 5. Niggli variation diagrams of the rapakivi granites contained in the Laitila, Wiborg and Salmi massifs.

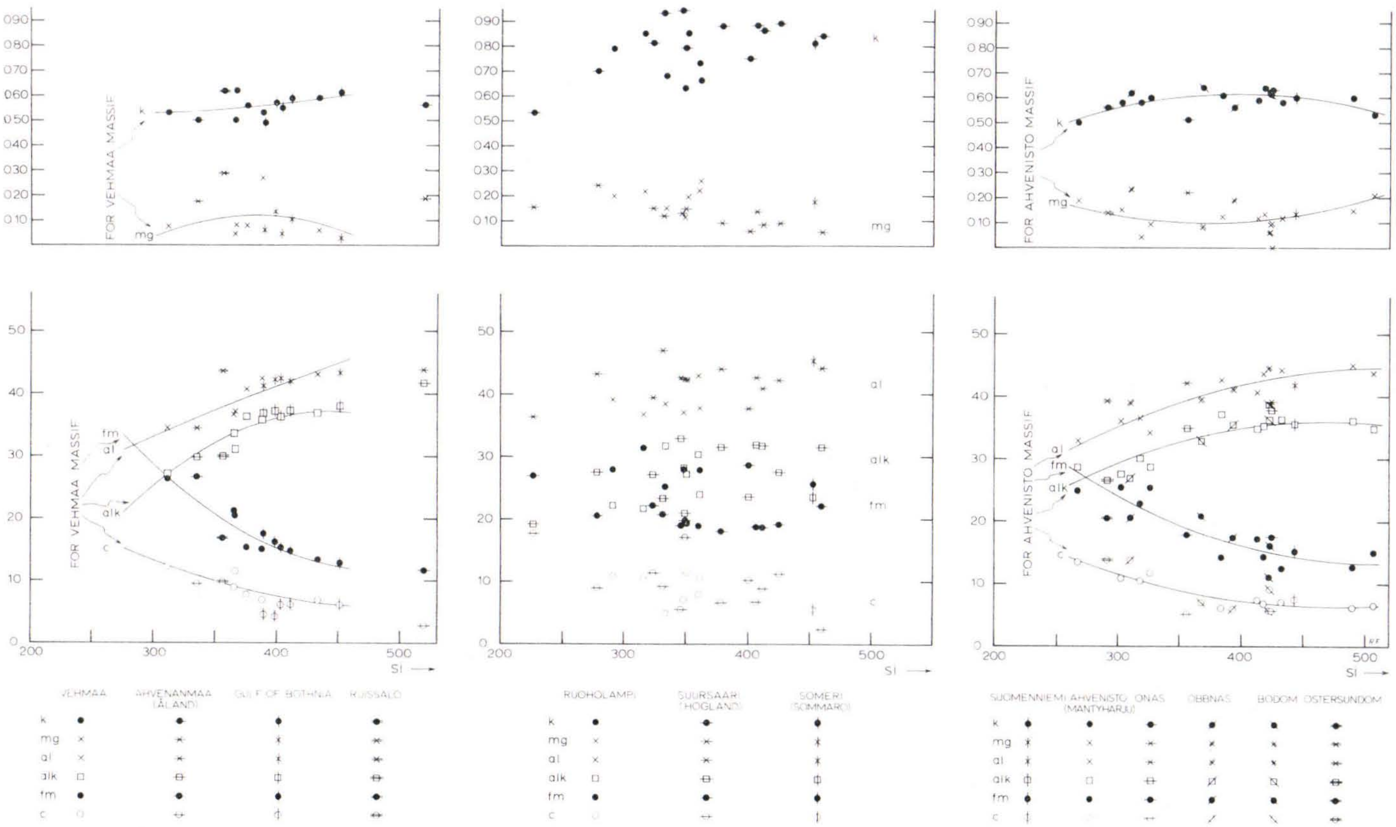


Fig. 6. Plots of Niggli values of the rapakivitic rocks from the occurrences as indicated in the figure and the regression curves for the Vehmaa and Ahvenisto massifs.

The reader's attention is called to Table 4, where the characteristic Niggli value *si* is given for each petrographic rock type and which aids the reading of both the Harker and Niggli variation diagrams. It appears from this table that the wiborgite rapakivi, the variety of rock prevailing in the Wiborg massif, has a somewhat lower average *si* value than the normal Laitila rapakivi (see Fig. 30), which is the predominant rapakivi variety in the Laitila massif.

Table 6.
Parabolic regression of Niggli values of rocks from the Laitila, Wiborg, Salmi, Vehmaa and Ahvenisto massifs

	a	*b*	*c*	*r*	S_{YXX^2}	N
Laitila massif						
k	0.3700	0.001055	—0.00000128	0.08729	0.05932	52
mg ...	0.0511	0.000795	—0.00000148	0.3060	0.07278	»
al	—19.88	0.2741	—0.0002852	0.7051	2.788	»
fm ...	96.45	—0.3337	0.0003210	0.7873	3.502	»
alk ...	—39.87	0.3212	—0.003345	0.8116	2.334	»
c	44.72	—0.1697	0.0001847	0.6556	1.613	»
Wiborg massif						
k	0.4463	0.000272	0.00000010	0.3653	0.07564	37
mg ...	—0.0211	0.001020	0.00000156	0.2516	0.05864	»
al	14.16	0.1051	—0.00009477	0.7788	2.447	»
fm ...	66.76	—0.2053	0.0001991	0.7845	4.002	»
alk ...	—27.46	0.2693	—0.0002835	0.9269	2.142	»
c	46.52	—0.1691	0.0001790	0.9021	1.559	»
Salmi massif						
k	0.6342	0.0000371	—0.00000060	0.4185	0.05216	81
mg ...	0.0706	0.0008452	—0.00000172	0.3341	0.08184	»
al	3.137	0.1633	—0.0001608	0.6434	2.333	»
fm ...	66.29	—0.1871	0.0001659	0.6478	3.544	»
alk ...	5.629	0.1021	—0.00007930	0.6642	2.385	»
c	24.96	—0.07838	0.00007430	0.6043	1.393	»
Vehmaa massif						
k	0.6558	—0.0009760	0.00000187	0.3826	0.05267	6
mg ...	—1.723	0.009623	—0.00001257	0.3146	0.1018	»
al	0.8490	0.1265	—0.00006415	0.8891	2.072	»
fm ...	126.7	—0.4723	0.0004848	0.9313	2.281	»
alk ...	—76.04	0.5090	—0.000572	0.9218	1.881	»
c	51.57	—0.1813	0.0001783	0.8334	1.673	»
Ahvenisto massif						
k	—0.3045	0.004631	—0.00000582	0.8382	0.02464	10
mg ...	0.8768	—0.004172	0.00000560	0.7395	0.03499	»
al	—8.537	0.2044	—0.0001964	0.9444	1.712	»
fm ...	78.64	—0.2590	0.0002563	0.9091	2.622	»
alk ...	—15.18	0.2178	—0.0002318	0.8910	1.915	»
c	45.09	—0.1635	0.0001722	0.9528	0.9366	»

a, *b* and *c* = regression constants; *r* = correlation coefficient; S_{YXX^2} = standard error of estimate; N = number of analyses from which the corresponding Niggli values were calculated and included in the regression analysis.

Regression analyses of Niggli values for the Laitila, Wiborg, Salmi, Vehmaa and Ahvenisto massifs were performed to find the curves with the best fit *si-k*, *si-mg*, *si-al*, etc. It was demonstrated experimentally that a parabolic regression is reasonably suitable for the present purpose. The regression analyses fitted the Niggli values in Figs. 5 and 6 to equations of the form $Y = a + bX + cX^2$ by the method of least squares. The regression constants *a*, *b* and *c* are given in Table 6. The correlation coefficient *r* and the standard error of estimate S_{YXX^2} are also given in the same table.

The regression curves thus derived are drawn in Figs. 5 and 6. This procedure very accurately holds the sum $al + alk + fm + c$ on the curves at 100 when the number of points is large, as, e.g., in the rocks of the Laitila and Salmi massifs. When the number of points is small, as, e.g., in the case of the Vehmaa and Ahvenisto massifs, the sum measured on the curves deviates somewhat from 100.

Fig. 7 is a composite diagram, where the regression curves of Fig. 5 are superimposed to allow a comparison of the Laitila, Wiborg and Salmi massifs to be made.

A study of the Niggli variation diagrams (Fig. 5) and the regression curves (Figs. 5 and 7) reveals differences in the Laitila, Wiborg and Salmi massifs, differences that were already found in the Harker variation diagrams but some of which are accentuated in the Niggli diagrams:

- The largest of the massifs, the Wiborg massif, has a considerably higher *c* and somewhat lower *al* value than the smaller Laitila and Salmi massifs.
- The differentiation of the Wiborg massif is more pronounced than that of the other massifs. As in the Harker diagrams, this can be seen owing to
  1. the compositional range in the Niggli variation diagram is larger in the Wiborg massif than in the other two massifs
  2. the possible composition gap, *si* = 350—420, of the Wiborg massif. This *si* range in the Laitila and Salmi massifs is densely occupied by analytic points.
- In connection with the study of the Harker diagrams it was pointed out that in the Wiborg massif K_2O increases and Na_2O decreases with increasing SiO_2, whereas in the Laitila massif the picture is not so clear; but in the Salmi massif, there is a marked decrease of K_2O and a slight increase of Na_2O with increasing SiO_2. These changes are beautifully accentuated in the Niggli variation diagrams. The *k* value of the Laitila massif is practically constant within the whole compositional range (see also the small correlation coefficient in Table 6). In the Wiborg massif, there is a clear increase of value *k* with increasing *si*; and in the Salmi massif, there is a clear decrease of *k* with increasing *si*.
- The Niggli *fm* curve bears the same features as the $FeO_{tot.}$ and MgO curves in the Harker diagrams. The Wiborg and Salmi massifs have similar *fm* curves, the Salmi massif recording slightly higher *fm* values than the Wiborg massif. With small *si* values, the Laitila rapakivis show higher *fm* values than the Wiborg and Salmi rapakivis. With increasing *si*, the *fm* of the Laitila rapakivis, however, decreases more rapidly and with *si* values higher than about 350, it shows considerably smaller *fm* values than the rocks of the other two massifs.

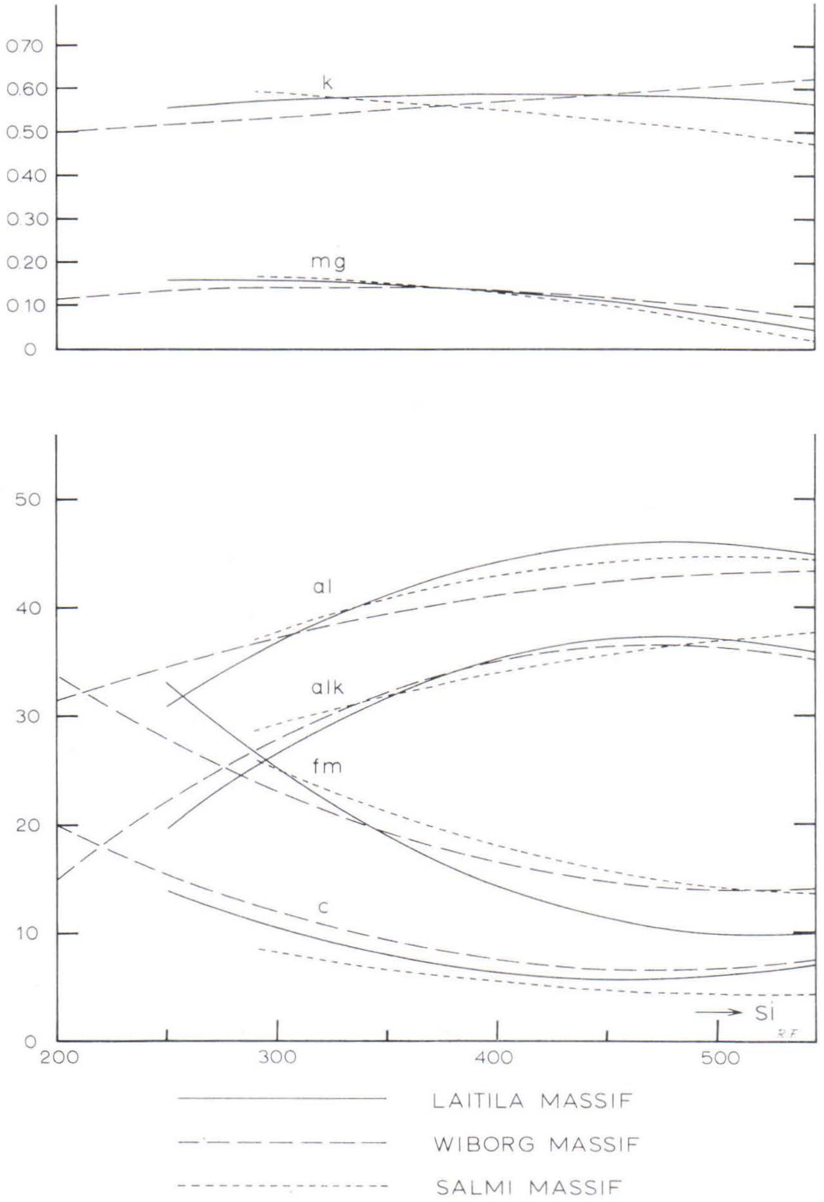


Fig. 7. Comparison of the Niggli variation diagrams of the rocks from the Laitila, Wiborg and Salmi massifs in the light of the regression curves of Fig. 5.

Data from other rapakivi occurrences are collected in Fig. 6. Even though the number of analyses of each occurrence is very limited, the figure allows some observations to be made.

In the light of the available analyses, the Vehmaa massif falls in composition between the Wiborg and Laitila massifs. The *alk* curve is similar to that of the Laitila massif; the *k* curve, however, is almost identical to that of the Wiborg massif. The *c* curve of the Vehmaa massif resembles closely that of the Wiborg massif (the Wiborg massif is characterized by a high CaO content and a high *c* value as compared with the Laitila and Salmi massifs). The *fm* curve, being parallel to that of the Laitila massif, records slightly higher values than the latter. As compared with the *fm* curve of the Wiborg massif, at *si* more than 370, the Wiborg massif records higher *fm* values, and at *si* less than 370, the Vehmaa massif records higher *fm* values. In regard to *al*, most of the points lie below the *al* curves of the Salmi and Laitila massifs, having thus the same tendency as the Wiborg massif, i.e., quite low *al* values. In regard to the *mg* figures, most of them show smaller values than the rapakivitic rocks on the average.

The Ahvenanmaa massif is represented by only two analyses. These are in accord with the rapakivitic composition. The normal rapakivi of Ahvenanmaa plots close to the regression curves drawn for the Vehmaa rapakivi, and the quartz porphyry of Ahvenanmaa deviates more from the standard curves introduced.

The same composite diagram also contains data on the porphyries of the Gulf of Bothnia, to the north of Ahvenanmaa. On the average, their Niggli values fall near the regression curves for the Vehmaa massif, the *c* values being exceptions that fall below the Vehmaa *c* curve. As compared with the Ruoholampi and Suursaari porphyries associated with the Wiborg massif (see below), the porphyries from the Gulf of Bothnia exhibit considerably lower *k* and *fm* values and considerably higher *alk* values. The *k* and *alk* values are such because of the higher Na_2O content in the porphyries from the Gulf of Bothnia. The *mg*, *al* and *c* values are the same in both porphyry groups.

The same composite diagram still contains the Niggli values of the rapakivitic Ruissalo quartz porphyry dike. Compared with rapakivitic composition, this rock is anomalous because of its very high *mg* value (resulting from contamination?).

The small occurrences of rapakivi around the Wiborg massif are grouped in the diagram on the right in Fig. 6. The chemical characteristics of these occurrences in the light of Niggli values may be summed up as follows:

- — The Suomenniemi rapakivi (only one analysis available) is in accord with the curves for the Wiborg massif.
- — The Ahvenisto massif shows the same general features as the Wiborg massif, the figure for *k*, however, being higher than that of the Wiborg massif; it is practically the same as in the Laitila massif.
- — The Onas (2 analyses), Obbnäs (2 analyses) and Bodom (3 analyses) granites are also in accord with the rapakivitic composition; owing to the very small

number of analyses and the scatter of points in the diagram, no other characterization of these granites can be given.

— The Östersundom quartz porphyry dike, even though cutting the nonrapakivitic Svecofennidic rocks and presumably being strongly contaminated, still bears the compositional character of rapakivis.

The midmost diagram of Fig. 6 contains the Niggli values of the volcanic and subvolcanic equivalents of rapakivi, associated with the Wiborg massif. If the Wiborg massif is taken as a standard of comparison, one can demonstrate that the Ruoholampi porphyries have very high *k* values (from 0.63 to 0.85) and somewhat higher *mg* and *fm* values and lower *alk* and *c* values than the Wiborg rapakivis on the average. The Suursaari and Someri quartz porphyries also have very high *k* values. The *mg* values are lower than those characteristic of the Wiborg rapakivi. Characteristic of these porphyries is their high *al* values when the *si* is low, indicating possibly early accumulation of feldspar. The *alk* values are conspicuously low. The *fm* values clearly increase at higher *si* values.

Most of the Suursaari analyses are quite old and must be regarded as unreliable. Wahl (1925, p. 89), after studying Lemberg's old analyses, states: »Alledings ist der Na_2O-Gehalt sämtlicher dieser Analysen ein ungewöhnlich niedriger und der K_2O-Gehalt auch höher als bei den entsprechenden Rapakiwianalysen, was auf einen metodischen Fehler in den Lemberg'schen Analysen hindeutet.»

Later on, in 1947, Wahl published some newer analyses of the quartz porphyries of Suursaari. In these, the *k* values are somewhat smaller than in the old analyses of Lemberg. Still these are considerably higher than in the actual granitic rocks of the Wiborg massif.

As most of the porphyries associated with the Wiborg massif have higher *k* values than the actual Wiborg rapakivi, it is clear that the volvanic counterpart of rapakivi crystallized from a magma with higher K/Na than the rapakivi granites.

In addition, the different massifs can be compared also by calculating the means of the available analyses of each massif. This has been done with the Laitila, Wiborg, Salmi, Vehmaa and Ahvenisto massifs, i.e., those massifs on which regression analyses were performed. The mean Niggli values are given in Table 7. In addition, this table contains for the purpose of comparison Sederholm's and Sahama's »averages,» Sahama's standard mixture (see p. 9) and Wahl's wiborgite and pyterlite magmas (see p. 10) as well as Niggli's rapakivitic magma type (see p. 7).

In the light of Table 7, it seems as if the Wiborg massif, with *si* = 361, were on the average somewhat more basic than the other massifs. This table also shows the low *al* values of the Vehmaa and Wiborg massifs, a feature already noted. Another feature, mentioned in the foregoing, the high *c* values of the Wiborg, Vehmaa and Ahvenisto massifs as compared with those of Salmi and Laitila massifs, is also noticeable in this table. Also the very low *fm* value of the Laitila massif is in accord with the foregoing observation. The mean *k* value is quite constant, ranging from 0.55 to 0.58. Sederholm's »average,» based on 9 rapakivi analyses, gave a considerable higher

Table 7.
The mean Niggli values for different rapakivi granite massifs compared with the »averages» from literature for rapakivi in general

	si	k	mg	al	fm	alk	c	N 1)
Laitila massif	408	0.58	0.124	43.6	14.7	34.5	6.8	52
Wiborg massif	361	0.56	0.133	39.1	20.0	30.9	10.1	37
Salmi massif	397	0.55	0.129	42.2	18.6	33.4	5.8	81
Vehmaa massif	373	0.56	0.101	39.0	18.6	33.4	9.0	6
Ahvenisto massif	386	0.58	0.133	39.9	18.4	33.0	8.7	10
Sederholm's »average» (Sahama 1945)	388	0.64	0.17	40	20	32	8	9
Sahama's »average» (op.cit.)	375	0.56	0.12	40	18	33	9	37
Sahama's standard mixture (op.cit.)	408	0.54	0.10	43	15	36	6	—
Wiborgite magma of Wahl (1925)	340	0.54	0.15	40	17	32	11	3
Pyterlite magma of Wahl (op.cit.)	470	0.62	0.15	40	17	35	7	3
The rapakivitic magma type of Niggli								
(1923)	380	0.50	0.27	40	18	33	9	—
(1936)	350	0.45	0.3	41	18	32	9	—

1) N, number of analyses from which the mean was calculated.

value (0.64). Sahama's »average,» $k = 0.56$, based on 37 analyses, is identical with the present data. Sederholm's »average» $mg = 0.17$ is certainly too high. Sahama's »average» mg is in accord with the present data. All the other figures representing Sederholm's and Sahama's »averages» are in accord with the present data.

The Niggli values of Sahama's standard mixture deviate quite considerably from the »averages.» The cause of the deviations was discussed on p. 9. It is curious that the mean composition of the Laitila massif corresponds quite nearly to Sahama's standard mixture.

Table 7 shows that Niggli's rapakivitic magma type deviates considerably from the average composition of rapakivis proper in two most characteristic points. Niggli's k value is too low and his mg value is at least twice as high as is characteristic of rapakivis. If a refinement in these respects is made, i.e., the k should be changed to 0.57 and the mg to 0.12, the rapakivitic magma type should be adequately characterized to be in accord with true rapakivi.

This is also an appropriate connection to return to Wahl's wiborgite and pyterlite magmas (Table 7). Wahl based the existence of these two magmas on data from the Wiborg massif. In the light of available chemical analyses there is a compositional gap in the Wiborg massif indicating the possible existence of two magmas. This gap may also be due to unsuccessful sampling. It may also indicate that prior to the emplacement, the rapakivi magma was not homogeneous but was either strongly differentiated or the rapakivitic melt generated was never thoroughly homogenized.

Table 8.
Mean normative composition of certain rapakivi massifs in the light of quartz and feldspars alone

	Qu	*Or*	*Ab* 1)	*Qu*	*Or*	*Ab*	*An* 2)	N 3)
Laitila massif	36.13	38.15	25.72	34.13	35.98	24.26	5.64	52
Wiborg massif	33.23	37.99	28.78	30.64	34.80	26.20	8.36	37
Salmi massif	36.71	35.86	27.42	34.89	34.01	26.03	5.08	83
Vehmaa massif	32.95	38.12	28.93	31.28	36.19	27.48	5.05	6
Ahvenisto massif	33.84	39.35	26.81	31.91	36.98	25.20	5.92	10

1) *Q*, *or* and *ab* of the CIPW norm recalculated as 100; now indicated as *Qu*, *Or* and *Ab*, respectively.
2) *Q*, *or*, *ab* and *an* of the CIPW norm recalculated as 100; now indicated as *Qu*, *Or*, *Ab* and *An* respectively.
3) N, number of norms included in the mean.

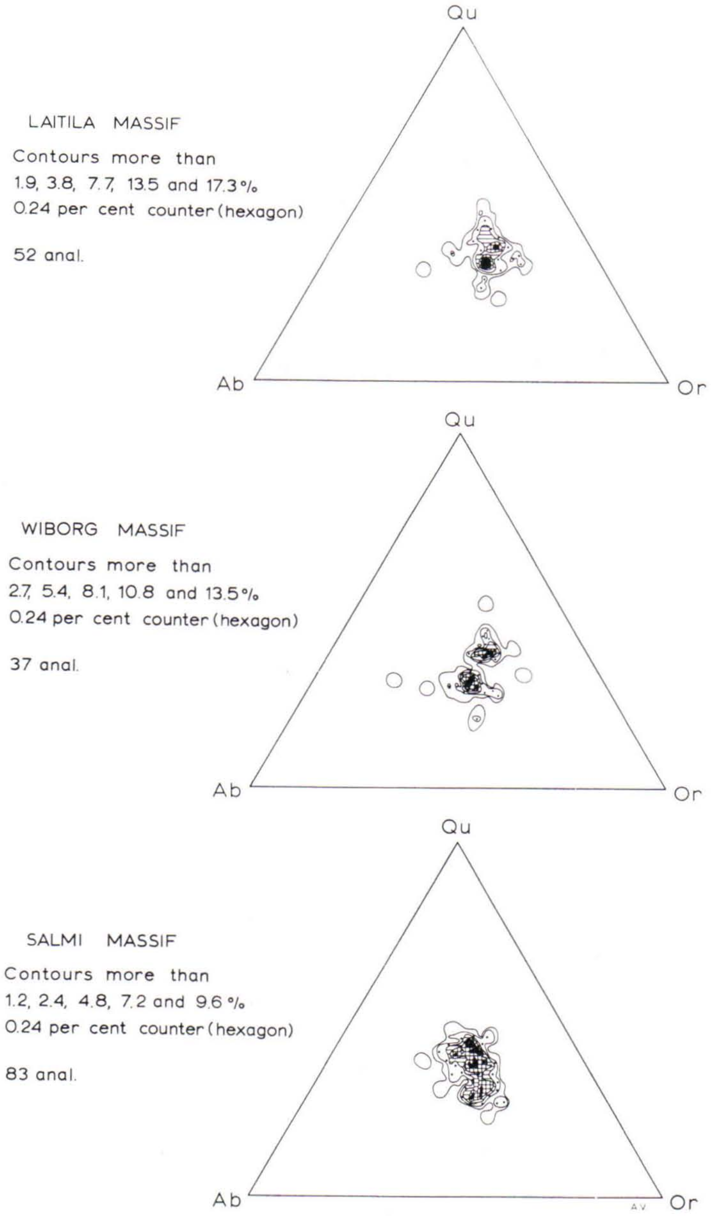
The more basic portions of the melt might have been generated deeper in the crust than the more acid portions. The subsequent history of the melts either led to the generation of rapakivi-textured rocks or to other textural varieties.

Qu-Or-Ab diagrams

In the CIPW norm calculation, certain oxides were excluded from the analyses to facilitate the making of comparisons. The standard oxides of the silicate analysis, SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, CaO, Na_2O, K_2O and P_2Os, were all included, while such oxides and elements as Li_2O, Rb_2O, BaO, SrO, ZrO_2, CO_2 and F, even though analyzed from many samples, were excluded. Especially the F and CO_2 seriously affect the normative anorthite.

The normative *Q*, *or* and *ab*, and *Q*, *or*, *ab* and *an* were recalculated as 100; the recalculated values are marked as *Qu*, *Or*, *Ab* and *An*. The artihmetic means arrived at for the Laitila, Wiborg, Salmi, Vehmaa and Ahvenisto massifs are given in Table 8. Contoured triangular *Qu-Or-Ab* diagrams for the Laitila, Wiborg and Salmi massifs were prepared. These are shown in Fig. 8. A study of these diagrams and Table 8 reveals only very small differences:

- — The Wiborg massif shows two distinct maxima corresponding to Wahl's wiborgite and pyterlite magmas.
- — The Laitila massif seems to be slightly poorer in *Ab* than the other massifs.
- — The Salmi massif is poorest in *Or*.
- — The general forms of the contoured areas in Fig. 8 are different for each massif. The longitudinal direction of the area, which is at the same time the direction of differentiation, or the direction to which the SiO_2*(Qu)* increases, projects in the Wiborg massif to the *Qu-Or* side, and in the Salmi massif to the *Qu-Ab* side of the triangle. The Laitila massif has in this respect an intermediate direction. This certainly reflects differences in the course of differentiation of the massifs.



LAITILA MASSIF
Contours more than
1.9, 3.8, 7.7, 13.5 and 17.3 %
0.24 per cent counter (hexagon)

52 anal.

WIBORG MASSIF
Contours more than
2.7, 5.4, 8.1, 10.8 and 13.5 %
0.24 per cent counter (hexagon)

37 anal.

SALMI MASSIF
Contours more than
1.2, 2.4, 4.8, 7.2 and 9.6 %
0.24 per cent counter (hexagon)

83 anal.

Fig. 8. Contoured frequency diagrams showing the normative composition of rapakivi granites from the Laitila, Wiborg, and Salmi massifs. *Qu*, quartz; *Ab*, albite; *Or*, orthoclase.

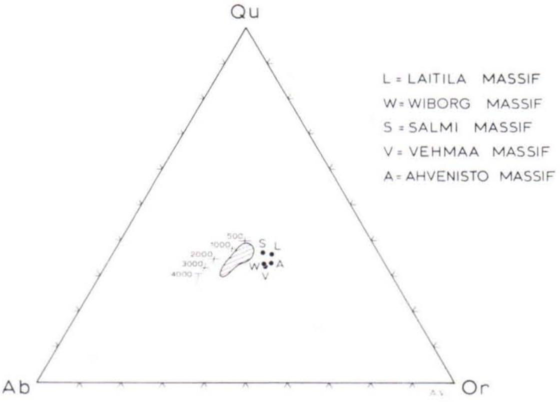


Fig. 9. The mean normative *Qu*, *Or* and *Ab* of the massifs indicated as compared with the maximum (ruled area) from the contoured frequency distribution diagram of the normative composition of 571 analyzed plutonic rocks (Tuttle and Bowen 1958) and with the position of the isobaric minimum in the haplogranitic system under different pressures (in kg/sq.cm) of water vapour.

Fig. 9 shows the mean *Qu-Or-Ab* in the triangular diagram. In the diagram, there is indicated an area that gives the maximum from the contoured frequency distribution diagram of the normative composition of 571 analyzed acid plutonic rocks (Tuttle and Bowen 1958). The end of the area indicated, towards the *Qu*, corresponds to the isobaric minimum in the haplogranitic system. With an increase of water pressure, the minimum shifts towards the *Ab*. With an increase in the anorthite content, the minimum shifts toward the *Qu-Or* side of the triangle (James and Hamilton 1969).

In many papers, it is emphasized (see, e.g., Savolahti 1956) that the normative composition of rapakivi is between the minimum and the *Or* corner. The means also fall into this area, as indicated in Fig. 9. The mean values are regarded here as representing undifferentiated rapakivitic magma.

Table 8 shows that the normative *An* (anorthite when $Q + or + ab + an$ is recalculated as 100) is highest in the Wiborg massif (in accord with the high CaO content in the Harker diagram and the high Niggli *c* value). In the foregoing treatment, the Vehmaa and Ahvenisto massifs also showed high *c* values. The Ahvenisto massif registers the second highest *An* in Table 8, and Vehmaa, on the other hand, the lowest. The discrepancy becomes understandable when studying the individual CIPW norm values (not reproduced in the present paper). In the case of the Vehmaa massif, the low *an* value is compensated for by *wo* in the norms.

Discussion on compositional differences

The diagrams introduced display small but clear differences both in composition and in course of differentiation in different occurrences of rapakivitic rocks.

One of the most important of the compositional differences is the high CaO and Na_2O in the Wiborg massif as compared with the Laitila and Salmi massifs. The small Ahvenisto and Vehmaa massifs resemble the Wiborg massif is this respect. At this point, attention is drawn to the common occurrence of the wiborgite texture in the rocks of the Wiborg massif and its sparseness and incompleteness in the rocks of the other massifs. Certainly, a sufficient amount of CaO is the first prerequisite for the wiborgite texture (to produce the plagioclase around alkali feldspar ovoids), the other certainly being the cooling rate of the massif and the fluxes present. The wiborgite texture is absent from the rocks of the smaller Ahvenisto massif, which cooled more quickly, even though its composition seems to favor the development of such a texture.

Another feature worth emphasizing here is the slightly lower silica content of the Wiborg massif than, e.g., of the Laitila and Salmi massifs. Also its bulk Al_2O_3 is possibly smaller than that of the Laitila and Salmi massifs.

Characteristic of the porphyries associated with the Wiborg massif is their extremely high K_2O/Na_2O ratio, which is beautifully shown in the Niggli diagrams. The porphyries of the Gulf of Bothnia, on the other hand, show lower Niggli *k* values.

The course of differentiation slightly differs from massif to massif. It has been demonstrated that in the Salmi massif, the K_2O/Na_2O decreases with increasing SiO_2 while in other massifs from which sufficient data are availabe, the ratio increases or is approximately constant. Another clear difference in the course of differentiation is the abrupt decrease of iron and magnesium with increasing silica in the Laitila massif as compared with the Wiborg and Salmi massifs.

The data at hand also suggest that the rate of differentiation is not the same in all the occurrences of rapakivitic rocks. Tentatively, it might be said that in the Wiborg massif the differatiation is most far advanced.

These differences in the bulk composition of different rapakivi occurrences cause ambiguity in the usage of names for certain rapakivi varieties. Thus, e.g., the normal rapakivi of the Laitila massif is texturally pyterlite, but in mineral and chemical composition differs greately from the pyterlite of the Wiborg massif. The pyterlite of the Wiborg massif is a SiO_2-rich (SiO_2 = 75—78 %) biotite granite. The pyterlite of the Laitila massif (= normal Laitila rapakivi) is a somewhat more basic (SiO_2 = 68—73 %) hornblende-biotite granite. The wiborgite of the Wiborg massif is in turn slightly more basic (SiO_2 = 65—72 %) than the normal Laitila rapakivi, but owing to its higher CaO content it has plagioclase mantles around the alkali feldspar ovoids. The wiborgite of the Salmi massif (SiO_2 = 67—74 %) only seldom shows well-developed plagioclase mantles around the ovoids because of its very low CaO content. The rock called pyterlite in the Salmi massif is rich in SiO_2 (73—76 %), like the pyter-

Table 9.
The petrographically different rapakivi varieties of the Laitila massif and their mineral composition

	Perthite	Quartz	Plagioclase	Biotite	Chlorite	Muscovite [6])	Hornblende	Fayalite [1])	Iddingsite [1])	Grunerite [1])	Fluorite	Zircon	Apatite	Opaques [7])	Monazite	Allanite	Carbonates	Anatase	Topaz
Normal rapakivi, greenish brown and red	M	M	M	m	c	vs	m	m/o	o	o	c	c	c	c	—	o	vs	o	—
Normal rapakivi, red and grey ..	M	M	M	m	c	vs	—	—	s	vs	c	c	c	c	vs	s	vs	o	—
Biotite rapakivi [3])																			
— coarse-grained	M	M	M	m	c	—	m/o	—	vs	—	c	c	o	c	vs	s	—	s	—
— medium-grained	M	M	M	m	c	vs	m/o	vs	vs	vs	c	c	o	o	s	s	s	s	vs
— aplitic	M	M	M	m	c	s	—	—	vs	—	c	c	o	o	s	—	—	s	—
— porphyry aplitic	M	M	M	m	c	—	—	—	—	—	c	c	o	o	—	—	—	—	—
— spotted	M	M	M	m	c	o	—	—	—	—	c	c	o	o	s	—	—	s	—
Hornblende rapakivi																			
— Tarkki granite [2])	M	M	M	m	c	—	m	o	o	—	c	c	c	c	—	—	—	o	—
Granite porphyry	M	M	M	m	—	—	m/o	s	o	—	o	c	c	c	—	—	—	—	—
Ytö granite	M	M	M	m	c	c	—	—	—	—	c	c	c	c	c	—	—	o	—
Autoliths in Ytö granite	M	M	M	m	c	c	—	—	—	—	c	c	c	c	c	—	—	o	—
Suutila granite ..	M	M	M	m	c	c	—	—	—	—	c	c	c	c	c	vs	—	o	—
Autoliths in S. gr.	M	M	M	m	c	c	—	—	—	—	c	c	c	c	c	—	—	o	—
Katinhäntä aplite	M	M	M	m	c	c	—	—	—	—	c	c	c	c	c	—	—	—	—
Dike rocks [4])																			
— pegmatitic ...	not studied																		
— medium-grained, granitic	M	M	M	m	c	o	s	—	s	—	c	c	o	o	—	—	—	—	—
— aplitic	M	M	M	m	c	o	o	—	o	—	c	c	o	o	—	—	—	—	—
— porphyry aplitic	M	M	M	m	c	—	—	—	—	—	—	o	—	o	—	—	—	—	—
— granite porphyritic ..	M	M	M	m	c	—	—	—	—	—	c	c	c	c	—	—	s	—	—
— quartz porphyritic ..	M	M	M	m	c	—	—	—	—	—	o	—	—	—	—	—	—	—	m
Schlieren, irregular inclusions and pools [5]) ..	M	M	M	m	c	—	m/o	o	o	s	c	c	o	o	s	s	s	—	—

Based on a study of more than 300 thin sections
M = major mineral present, > 10 %.
m = minor mineral present, 2—10 %.
c = characteristic accessory mineral; found in practically every thin section studied.
o = occasionally discovered accessory mineral; found in approximately one out of two thin sections studied.
s = seldom discovered accessory mineral; found in only a small number of thin sections studied.
vs = very seldom encountered accessory mineral; found in only a few thin sections studied.
— = not detected.

lite of the Wiborg massif. Its K_2O and CaO contents, however, are much lower than in the pyterlites proper of the Wiborg massif. Similar differences are to be found in certain other varieties, too. Therefore, the author suggests that the usage of such rock names as wiborgite, pyterlite, and tirilite should be restricted to the Wiborg massif only. As textural terms, the wiborgite texture and the pyterlite texture could well, of course, be used outside the Wiborg massif.

LAITILA MASSIF

While most of the new, previously unpublished chemical analyses are from the Laitila massif, about which no comprehensive description of the different varieties of rock and their mutual relations is available, this massif will be described more thoroughly than the other occurrences. However, the petrochemistry of rapakivis being the theme of this thesis, the rocks of the Laitila massif will be described only in the scope regarded as necessary. A separate study on the petrography and mineralogy of the Laitila massif is in progress.

Description of rock types and analytic material

Table 9 serves as a guide for the different petrographic rapakivi varieties. All these varieties are granitic in composition, granitic in the sense of Streckeisen's terminology (1967). The number of chemically analyzed samples amounts to 52. The localities for these 52 samples are indicated in the sketch map of Plate 1 which also gives an overall picture of the Laitila massif. Of these 52 chemical analyses, 35 are new. The list of analytic samples is given in Appendix 1, the chemical analyses in Appendix 2.

Table 9; additional remarks:

1) Fayalite, iddingsite, and grunerite often occur together. Their occurrence is confined to the dark and darkish rapakivi varieties, both of normal and even-grained and granite-porphyritic types.

2) Tarkki granite contains, in addition to the minerals listed, danalite and perrierite or chevkinite (Haapala 1974).

3) Väkkärä granite contains fluorite, zircon, anatase, monazite, xenotime, bastnaesite, cassiterite, columbite, and thorite (Haapala, op. cit.).

4) and 5) Mostly dikes, lenses, and schlieren of rapakivi cutting or occurring as inclusions in another rapakivi variety; follows its host rock's colour and mineral composition to some extent. Thus, the even-grained irregular granite inclusions in dark-coloured normal rapakivi (fayalite-bearing hornblende granite), are often fayalite- and hornblende-bearing, too.

6) Muscovite, white mica when it occurs as large flakes. In addition, sericite occurs in every thin section studied as inclusions in plagioclase.

7) The opaques are mainly magnetite and ilmenite; occasionally, in addition, pyrite, pyrrhotite, chalcopyrite, molybdenite, and galena.

Normal Laitila rapakivi

The bulk of the Laitila rapakivi massif consists of normal Laitila rapakivi (Figs. 10 and 11), which is similar in texture to the pyterlite of the Wiborg massif but is closer in mineral and chemical composition to wiborgite than pyterlite. The ovoidal texture is well developed, plagioclase mantles around alkali feldspar avoids are sparsely present and when they do occur are thin (Fig. 12). The ovoids measure from 2 to 4 cm in diameter on the average; in places, there are varieties with larger ovoids; and in other places, varieties are met with that have smaller ovoids; often also the ovoids are subangular and grade over to varieties with angular alkali feldspar phenocrysts.

In respect of colour, the normal Laitila rapakivi varies. The prevailing variety is a dirty greenish brown, which in places turns quite dark greenish brown, in places red and more rarely gray. It is highly probable that the different colour varieties represent different intrusive phases. In mineral composition, there are clear differences, too. The brownish variety is a hornblende-biotite rapakivi, while the red variety is mostly a biotite rapakivi, even though a few samples of red hornblende-biotite rapakivis have been encountered. The chemically analyzed grayish granite porphyritic normal rapakivis are biotite rapakivis.

In addition to the colour varieties, textural varieties of the rock also occur. The variation in ovoid size has already been discussed. Near the contacts against the country rocks of the massif, in places at a distance of no more than 100—200 m from

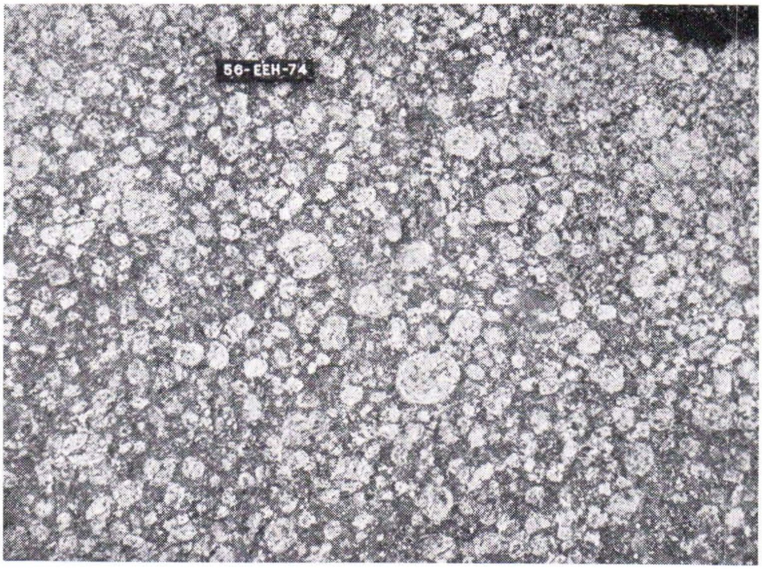


Fig. 10. A typical occurrence of normal Laitila rapakivi. Two km southwest of sampling site No. 39 in Plate 1. Karjalankylä, Karjala. 1/9.6 natural size. Photo: Erkki Halme.

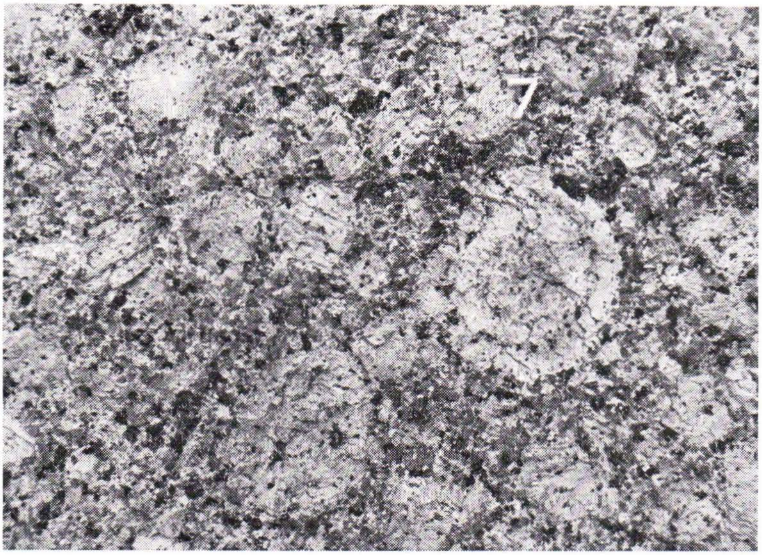


Fig. 11. Pyterlite texture in normal Laitila rapakivi. 1.5 km northwest of sampling site No. 41 in Plate 1. Katinhäntä, Laitila. 1/2.8 natural size. Photo: Erkki Halme.

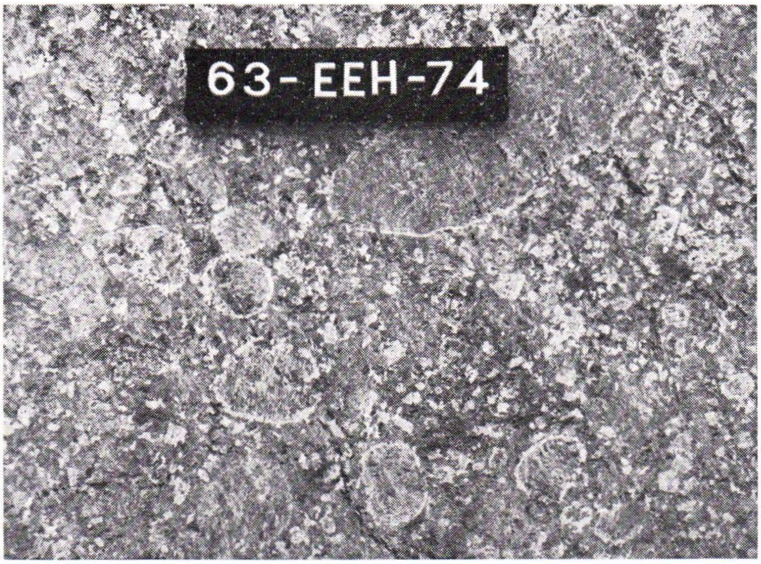


Fig. 12. Poorly developed wiborgite texture in normal Laitila rapakivi. 700 m east of sampling site No. 7 in Plate 1. Lemmi, Mynämäki. 1/2.8 natural size. Photo: Erkki Halme.

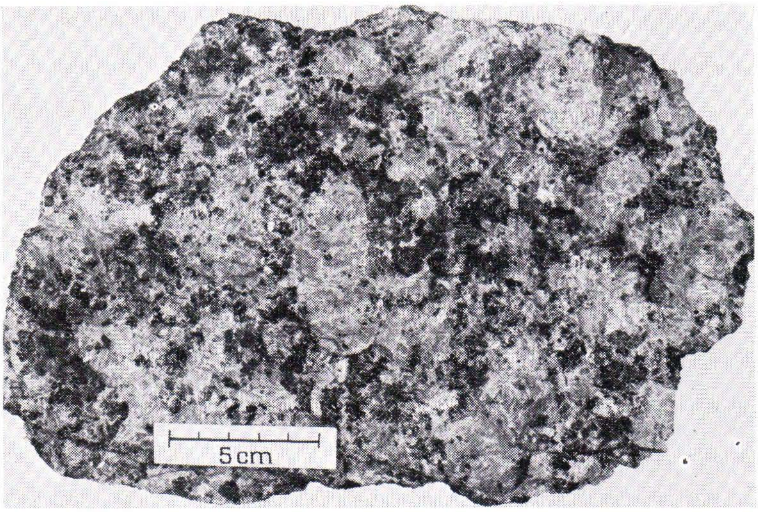


Fig. 13. Coarse-porphyritic Kokemäki granite. Sampling site No. 11 in Plate 1. Peipohja, Kokemäki. Photo: Erkki Halme.

the contact, the ovoids can often be seen to become smaller and smaller as well as sparser. In many places, a contact zone some few tens of meters broad and composed of a medium- and even-grained granite is found occurring against the nonrapakivitic country rock. This »chilling» of rapakivi against its country rock is not to be found everywhere.

Another textural variety to be found near the contacts is the granite porphyritic contact variety, which also forms zones tens of meters broad in places against the country rock. In same places close to the contact, granite porphyry cutting the normal rapakivi has also been encountered. In these cases, the rock represents a later intrusive phase or a result of autointrusion.

Textural varieties of normal Laitila rapakivi similar to those just described are met with also in the inner parts of the massif. These inhomogeneities may be due in part to the proximity of the roof of the massif. As a matter of fact, in the central parts of the massif there occurs a small roof(?) breccia.

In places, there a gradual change seems to take place from normal rapakivi to other locally prevailing rapakivi varieties. In the grouping of the analytic material, the transitional types have caused some difficulty.

The chemically analyzed rapakivi granite samples Nos. 3—16 (Appendix 1) have been grouped among the normal rapakivi. In the following, a subdivision of this group is made.

Nos. 4—7 are all of the dirty-greenish-brown variety. They are hornblende-biotite rapakivis, which besides the characteristic accessory minerals of normal Laitila rapakivi (fluorite, zircon, apatite, and opaques) also contain fayalite, its alteration

Appendix 4, contd

	Ytö granite and related rocks								
	33	34	35	36	37	38	39	40	41
La	103	105	52	66	85	117	109	138	133
Ce	230	215	120	132	205	257	253	313	911
Nd	102	78	52	51	89	126	111	149	386
Sm	17.1	15.4	8.62	11.6	13.1	18.8	15.5	20.3	21.6
Eu	0.91	0.54	0.73	0.57	0.91	0.92	0.69	0.77	3.20
Gd	—	—	8.03	—	11.2	—	12.5	—	—
Tb	1.79	1.5	0.94	1.1	1.71	2.1	1.92	2.4	7.66
Dy	14.3	11.6	6.90	5.6	11.8	13.0	13.4	11.8	15.2
Tm	1.48	1.3	0.87	0.9	1.49	1.6	1.53	1.5	5.52
Yb	5.03	4.0	2.18	2.6	5.44	6.3	5.35	6.7	21.7
Lu	1.11	0.9	0.83	0.6	0.75	1.2	1.00	1.0	1.39
Hf	9.28	8.1	4.64	6.2	10.2	8.6	15.6	10.1	37.3
Th	51.5	67.5	30.1	41.6	46.2	42.2	50.6	43.5	143
U	6.26	6.7	3.65	2.6	9.36	8.6	10.5	5.1	6.96
Hf/Zr ...	0.040	0.039	0.036	0.044	0.038	0.033	0.038	0.028	0.107
Th/U	8.23	10.07	8.25	16.0	4.94	4.91	4.82	8.53	20.55

Appendix 4, contd

	Väkkärä granite	Dike rocks			Mean		
	48	49	51	52	53	Standard deviation	Number of determinations
La	40	160	120	7.6	100	35	38
Ce	93	351	271	19.0	227	135	38
Nd	34	169	133	4.8	99	58	38
Sm	7.8	24.1	18.5	0.3	16.4	5.4	38
Eu	0.20	0.59	1.38	0.06	1.17	0.79	38
Gd	—	—	—	—	14.2	5.2	8
Tb	2.2	3.1	2.3	0.24	2.14	1.14	38
Dy	14.4	17.9	14.9	1.6	13.6	5.2	38
Tm	—	1.8	1.5	—	1.55	0.82	36
Yb	18.6	8.2	6.4	2.7	7.1	3.9	38
Lu	3.0	1.5	1.2	0.7	1.17	0.48	38
Hf	4.7	9.9	10.9	10.4	11.5	6.1	38
Th	22.8	36.8	39.4	18.2	38.8	24.7	38
U	8.9	4.2	4.0	6.3	6.14	2.66	38
Hf/Zr ...	0.047	0.047	0.032	0.433	0.043		
Th/U	2.56	8.76	9.85	2.89	6.32		

Fig. 14. Granite porphyry. Sampling site No. 15 in Plate 1. Haukkavuori, Säkylä. Photo: Atso Vorma.

product iddingsite, and grunerite. Allanite is quite often seen, as well as anatase, which is an alteration product of ilmenite. Concerning these samples, two observations merit mention. No. 4 is of a small-ovoidic variety, No. 5 from quite close to the contact of the massif (90 m).

No. 13 belongs together with Nos. 4—7. It is, however, a medium-, even-grained dirty-greenish-brown contact variety taken 60 m from the contact of the massif.

Nos. 3 and 12 are of pale-red normal Laitila rapakivi, No. 12 in fact a transitional variety between normal rapakivi and even-grained rapakivi. Both are hornblende-biotite rapakivis with the same accessory minerals as those listed in the foregoing. Fayalite, iddingsite and grunerite, however, are missing. This also accounts for the colour difference. No, 3, in addition, deserves a special note because of the bluish colour of the quartz.

No. 11, consisting of porphyritic Kokemäki granite (Fig. 13), is here classified with the normal Laitila rapakivi, from which it is separated by the rift valley of Satakunta filled with Jotnian sandstones. The rock is salmon red. The alkali feldspar phenocrysts are in part subangular, in part angular and only rarely ovoidic in form. The rock is a hornblende-biotite granite, containing the typical accessory minerals of rapakivi.

Nos. 8—10 have been described as normal Laitila rapakivi. The subgrouping remains open.

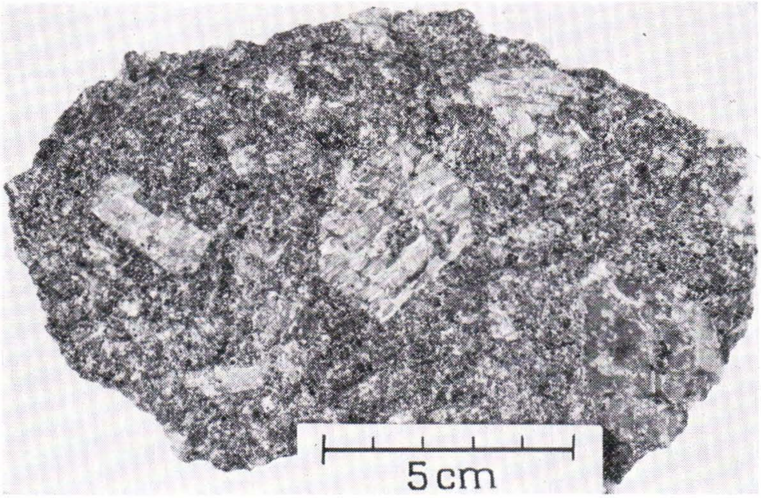


Fig. 15. Granite porphyry. Sampling site No. 14 in Plate 1. Sydänmaa, Eurajoki. Photo: Erkki Halme.

Nos. 14—16 have been designated as rapakivi granite porphyries because of their small-grained groundmass (Fig. 14). The ovoid-shaped, in places angular (Fig. 15) alkali feldspar phenocrysts are not so densely packed as in the normal rapakivi. All these rocks are biotite rapakivis, gray, or reddish gray in colour. Besides the characteristic accessory minerals of rapakivi (fluorite, zircon, apatite, opaques), Nos. 14 and 15 contain, in addition, monazite and anatase, No. 15 also allanite.

Sample No. 16 was taken some meters from the contact of the massif. The relation of the other two samples, Nos. 14 and 15, in respect to the contact of the massif is unknown. They are presumably from near the roof contact of the massif.

Biotite rapakivis

A minor part of the Laitila massif consists of rapakivi varieties that in their textural features deviate so much from the normal Laitila rapakivi as to have been designated by special names. These granites form bodies measuring from some tens of centimeters to several kilometers in diameter. Some of these are evidently of an autolithic nature formed from magma chilled earlier and brecciated by the same magma. A part certainly is a result of early segregation. Some of the biotite granites were evidently produced by autointrusion. Finally, many of the biotite granite bodies, such as, for instance, those of Ytö and Suutila, formed from completely different intrusion phases of rapakivi from those out of which the normal Laitila rapakivi crystallized. Certain of these granites are described under separate headings.

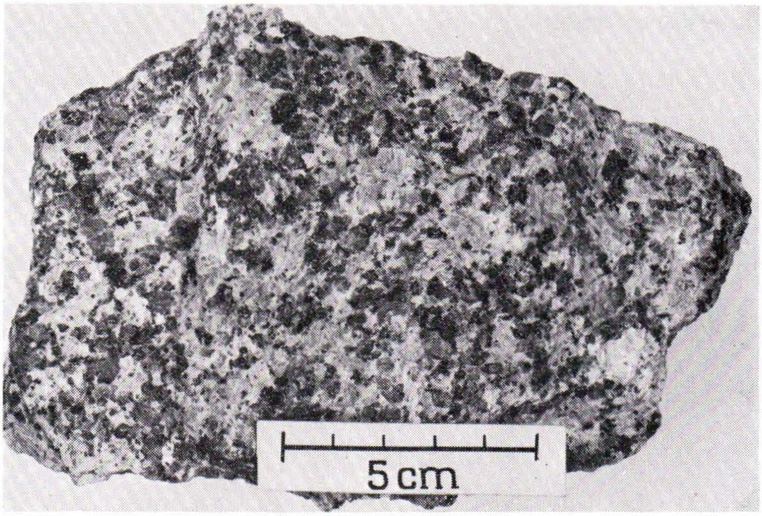


Fig. 16. Lellainen granite. Sampling site No. 17 in Plate 1. Lellainen, Eura. Photo: Erkki Halme.

In texture these rapakivis grade from even-grained to porphyritic, from fine-grained to coarse-grained. A common feature is that they are mostly biotite granites. A few of them, indeed, contain some hornblende; in addition, a few contain fayalite, too. Nevertheless, all have been grouped among biotite granites.

Table 9 gives the mineralogically characteristic features of these granites.

The most important of the different bodies of biotite granite will now be characterized briefly.

The Lellainen granite (see Plate 1) is a large mass of homogeneous, coarse- to medium-grained rapakivi (Fig. 16) containing light-reddish alkali feldspar and bluish milky quartz. In places, the rock grades over to a small-grained composition. Fluorite and zircon are the characteristic accessory minerals. Apatite, opaques, monazite and muscovite occur here and there, while allanite and anatase have been encountered in only a few thin sections. Chemical analysis No. 17 is of a typical representative of Lellainen granite.

The field data indicate that the Lellainen granite belongs to the same intrusive phase as the surrounding normal Laitila rapakivi. In places, a gradual change to this phase has been observed to take place via hornblende-bearing varieties of Lellainen granite. In some instances, the change is rather abrupt, and in places a seam of granophyre occurs between the two granites, indicating local age differences in the rocks.

The Elijärvi granite (Fig. 17) is rather similar to the Lellainen granite. It is slightly darker than the latter, and the quartz is also dark and smoky, not milky blue as in the Lellainen granite.

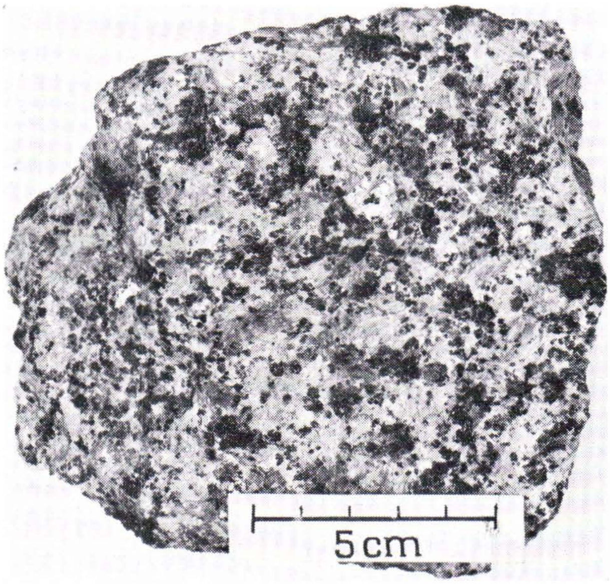


Fig. 17. Elijärvi granite. Sampling site No. 20 in Plate 1. Elijärvi, Yläne. Photo: Erkki Halme.

The Elijärvi granite is a typical biotite rapakivi containing hornblende, which was detected only in one of the eight thin sections investigated. Fluorite, zircon, apatite and opaques are the characteristic accessory minerals. Monazite was detected in two of the thin sections; these were devoid of apatite. Allanite was seen to be present in 50 % of the rocks studied.

Anal. No. 20 is of a typical representative of Elijärvi granite.

Also the Elijärvi granite undergoes in places a gradual change to normal Laitila rapakivi, but in places the transition is abrupt, with a granophyre occurring between the two rocks.

The Honkilahti granite, a narrow body about 9 km long located east and northeast of Honkilahti church, is almost identical to the Lellainen granite with its bluish, milky quartz and light-reddish alkali feldspar. A gradual transition to normal rapakivi is to be observed, at least in places. Anal. No. 12, discussed in connection with normal Laitila rapakivi, represents a variety between Honkilahti granite and normal Laitila rapakivi.

The Honkilahti granite grades from fine-grained, in places granite porphyritic, to coarse-grained. A quite coarse-grained variety seems to prevail. Near the contact of Jotnian diabase, a micrographic texture is often to be observed in the granite.

As for mineral composition, the four accessory minerals, fluorite, zircon, apatite and opaques, which are characteristic of rapakivi, also characterize the Honkilahti granite. Monazite was detected in three, allanite in one, and anatase in one of the 12 thin sections studied. Analyses Nos. 18 and 24 are of typical Honkilahti granite.

The Lellainen-type, even-grained rapakivi with the bluish milky quartz is met with again in the biotite rapakivi body of Neittamo, SW of Eura, from which granite the chemical analysis No. 22 was done. There is a small, interesting occurrence of Lellainen-type rapakivi about 850 m west of the Hinnerjoki church. In a road cut, there occurs either the roof contact of a Lellaine-type granite cupola against the normal Laitila rapakivi, or a thick, subhorizontal, upward convex dike of Lellainen granite, which cuts the normal rapakivi. Here the contact relations clearly show the Lellainen-type granite to be younger than the normal rapakivi. Chemical analysis No. 19 is of this Lellainen-type rapakivi, met with about 2 m from the contact. Between this occurrence and the contact there is a broad, banded, chilled contact variety of Lellainen-type rapakivi. The contact line itself is sharp. Note should here be taken of the fact that analysis No. 3, representing normal Laitila rapakivi, is of a sample some few meters from the contact against the even-grained granite mentioned in the foregoing.

To sum up, all the rocks for analyses Nos. 17—20, 22 and 24 are very similar in appearance. All can be described as Lellainen-type rapakivis. In places, they seem to change gradually to normal Laitila rapakivi, but in other places the contact is sharp. In certain places, a contact variety occurs against the normal Laitila rapakivi. In the present author's view, all these features can be explained if these biotite granites are taken as a result of differentiation of normal rapakivi (magma) and autointrusion.

Distinct from the Lellainen-type rapakivi described are the following small occurrences of biotite rapakivi. The small Turajärvi granite, northeast of Lappi village, changes gradually(?) into normal rapakivi. The rock is inhomogeneous, in places even-grained and in places with scattered ovoids turning into porphyry aplite; in certain instances, the ovoids increase in quantity and the grain size of the matrix decreases to justify designating the rock as granite porphyry. The chemically analyzed sample, No. 21, closely resembles granite porphyry. There are not as many alkali feldspar phenocrysts (ovoids) present, however, as in the granite porphyries proper. The chemically analyzed rock is a red biotite rapakivi. Fluorite, zircon, apatite and opaques occur as accessory minerals.

Also distinct from the Lellainen-type granite and also from the afore-mentioned Turajärvi granite is the coarse, even-grained Haaro granite, located about 8 km to the east from Laitila church and forming a granite body more than one km in diameter. The granite contains in places a few pyterlitic, in places even wiborgitic, ovoids per sq.m. It is a brownish-red biotite granite, in which also hornblende is detected in small amounts in two of the four thin sections investigated. Among the accessory minerals, the fluorite, opaques and zircon might be taken as characteristic. Apatite is detected only in one thin section. Also iddingsite, calcite, and anatase are sparsely present. A representative analysis of Haaro granite is given in Appendix 2, No. 26.

The Haaro granite has a sharp, abrupt contact against the normal rapakivi. The

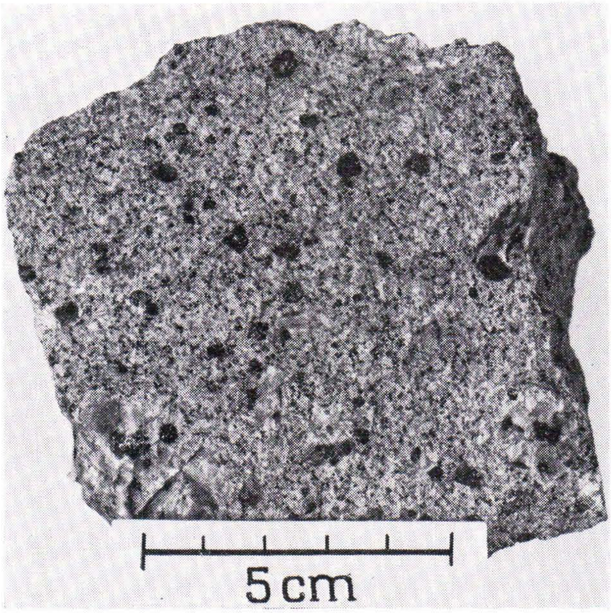


Fig. 18. Porphyry aplite. Note the large alkali feldspar ovoid in the lower left corner of the sample and the small darkish quartz phenocrysts. Sampling site No. 27 in Plate 1. Latvajärvi, Eura. Photo: Erkki Halme.

relative ages of these two rocks cannot be deduced on the basis of the contacts so far exposed.

In the introductory comments on the biotite rapakivis, different kinds of occurrences were described. The next example is assumed to represent a small autointrusion body in normal Laitila rapakivi. Some 5.5 km northeast of Laitila, in a dirty-greenish-brown variety of the normal rapakivi, there occurs a subhorizontal schlieren, measuring up to 1 m in thickness, of medium-grained, in places fine-grained, dark rock, like the typical tirilite of the Wiborg massif. The contacts against the normal rapakivi are sharp. On exposure the schlieren could be interpreted as either a cutting dike or an enclave. The mineral composition is the same as in the country rock, i.e., it is a hornblende-biotite granite with abundant fluorite and some zircon, apatite (rare), and opaques as accessories. In addition, fayalite, iddingsite, grunerite and calcite are present in small amounts. Its chemical analysis, No. 25, shows its bulk composition to be near that of the biotite rapakivis, but not even nearly approaching normal rapakivi. Also its composition contradicts the assumption that it was an early segregation in normal rapakivi. If an autointrusion origin for this body is accepted, the mineralogical similarity and at the same time, the differences in bulk composition of the rocks are understandable.

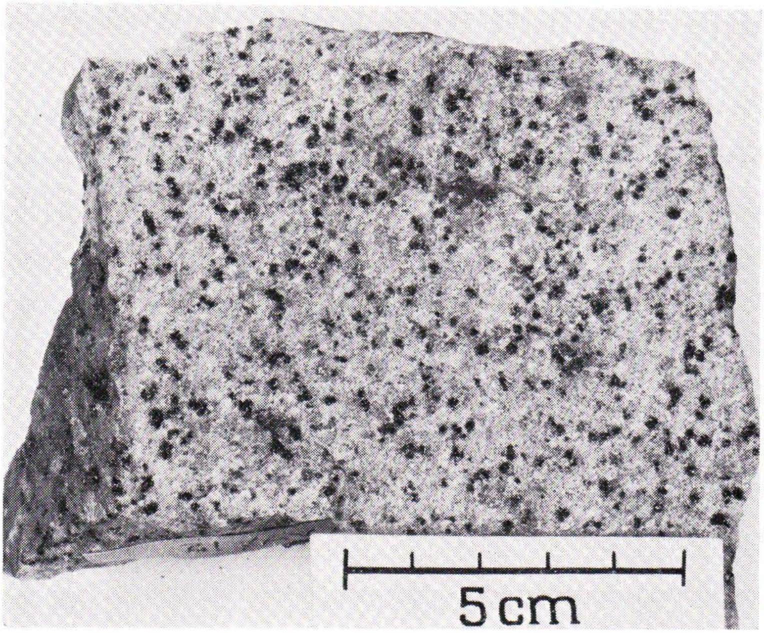


Fig. 19. Fine-grained spotted granite. Sampling site No. 29 in Plate 1. Kodisjoki. Photo: Erkki Halme.

Certain occurrences of even-grained biotite rapakivi presumably belong to different intrusive phase(s) from any normal Laitila rapakivi. As an example of chemically analyzed rock, anal. No. 23, is the small occurrence of topaz-bearing medium-grained, even-grained red rapakivi, located 9 km west of the south shore of Elijärvi. The granite contains plenty of fluorite, with zircon, muscovite and monazite as additional characteristic accessory minerals. Apatite and opaques are seldom met with. In appearance, the rock is identical with the even-grained varieties of the well-known Väkkärä granite, also a topaz-bearing rapakivi, to be described later.

To the east of the Lellainen granite body, the small-ovoidic normal Laitila rapakivi gradually changes, over a distance of a few meters, to an even-grained, in places porphyry-aplitic, reddish-brown rapakivi. In grain size, this granite in most cases varies from fine, aplitic, to medium. All the varieties are biotite rapakivis with fluorite and zircon as accessories, occasionally also muscovite, opaques, apatite and anatase. The chemically analyzed porphyry aplite, No. 27, contains scattered alkali feldspar insets up to 1 or 2 cm in diameter, situated 5—10 cm apart, and smaller quartz phenocrysts (up to 5 mm in diameter), at intervals of 1—2 cm, in a fine-grained red matrix (Fig. 18) as well as the accessory minerals fluorite, zircon, muscovite and monazite.

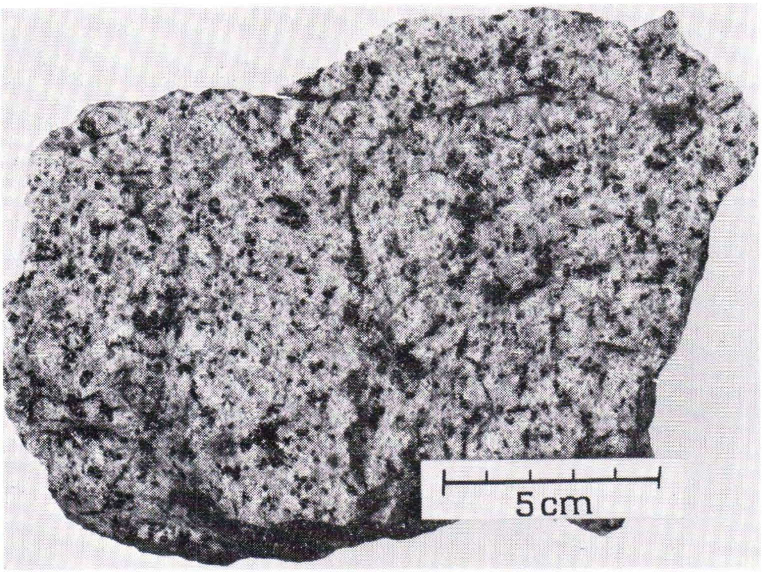


Fig. 20. Medium-grained spotted granite with, in part, plate-like aggregates of biotite. Sampling site No. 31 in Plate 1. Lamssijärvi, Yläne. Photo: Erkki Halme.

The mode of occurrence (dike or inclusion) and other details about the chemically analyzed aplite (anal. No. 28), published by Eskola, is unknown.

So-called spotted granites form a special group among the biotite rapakivis. It is characteristic of these granites that in the usually small-grained, occasionally medium-grained matrix, there are abundant black biotite spots. In the fine-grained varieties (Fig. 19), these spots measure up to 1—2 mm in diameter; in the medium-grained biotite rapakivis (Fig. 20), up to 1 cm in diameter. The occurrences of spotted rapakivi are small. The rock evidently is younger than the normal rapakivi. In places, as, for instance, near Lamssijärvi, it grades over to a small-grained rapakivi without any biotite spots.

For the mineral composition of the spotted granites, see Table 9. Two of the chemical analyses, Nos. 29 and 30, are of specimens from the small Kodisjoki occurrence. Here the rock is a homogeneous, small-grained reddish granite. Analysis No. 31 is of the medium-grained spotted granite of Lamssijärvi, and No. 32 from Suontaka.

Ytö granite and related rocks

Certain rapakivi granites in the southern part of the Laitila massif, viz., the Ytö granite, Suutila granite and Katinhäntä aplite are clearly younger than the surrounding normal rapakivi. Their emplacement took place quite probably by the mechanism of underground cauldron subsidence. In mineral composition, these granites possess certain characteristic features distinct from those of other rapakivis of the Laitila massif.

All these granites are biotite granites, even though, as will be shown, their bulk composition corresponds to that of hornblende-biotite granite. In addition to the characteristic accessory minerals of most Laitila rapakivis (fluorite, zircon, apatite and opaques), accessory muscovite and accessory monazite characterize these rocks (see Table 9). On account of the high monazite content, the biotite of these granites contains inclusions with pleochroic haloes in unusually large amounts. These haloes have attracted researchers to make special studies (Kaitaro 1955). Plagioclase usually shows a very well developed fine-scaled zoning. The colour of these granites is gray, while most of the other rapakivis are reddish brown or red.

Ytö granite appears in two major varieties, i.e., a centrally situated small-grained granite and another variety situated on the margin against the country rock, the normal rapakivi in this case. The aplitic central granite (chemical analysis No. 34) has small, lath-shaped, white alkali feldspar phenocrysts, measuring up to 0.5—1 cm in diameter, varying in amount from place to place. Here and there alkali feldspar ovoids, from 2 to 5 cm in diameter, are encountered — their frequency of occurrence is only a few per sq.m. Approaching the contact area, the feldspar laths increase in amount and size (1—3 cm) along with a coarsening of the groundmass (medium-grained). Close to the contacts, in the marginal variety, the alignment of the laths parallel to the contact is quite marked (Fig. 21). The contact line itself is sharp (Fig. 22). Large alkali feldspar ovoids are scattered in this contact zone. The breadth of the contact zone varies from tens of meters to some hundreds of meters. Analysis No. 33 is of a sample from this contact zone.

A feature peculiar to the Ytö granite is the presence of enclaves (Figs. 23 and 24) of a very fine-grained gray rock (analyses Nos. 35 and 36). They measure from a few centimeters to tens of centimeters in diameter. Mostly they are oval in shape, the longest axis running parallel with the alignment of the alkali feldspar laths and at the same time parallel with the contact. In some of the enclaves scattered alkali feldspar phenocrysts, similar to those in the Ytö granite, are encountered (Fig. 24). The mineral composition of the enclaves is the same as in the host Ytö granite. The author interprets the enclaves as autoliths that had originally been chilled Ytö granite.

The samples for analyses Nos. 33 (marginal Ytö granite) and 35 (autholith) are taken from the same place, only about 20—30 cm apart.

The Katinhäntä aplite forms an elongated body about 6 km long running east-west. This body is rimmed by a marginal, more or less porphyritic rock called Suutila granite (Fig. 25). The width of this rimming granite body varies from a few meters to 800 meters. In places, as in the southwestern part of the aplite, large inclusions (screens) of normal Laitila rapakivi are found.

In appearance, the Katinhäntä aplite corresponds closely to the small-grained central Ytö granite, the marginal Suutila granite to the marginal Ytö granite. The two granites in the Katinhäntä—Suutila composite body have been mapped and

Fig. 21. Typical occurrence of the marginal Ytö granite with well-developed parallelism of the alkali feldspar laths. Sampling site No. 33 in Plate 1. Kusni, Laitila. Photo: Atso Vorma.

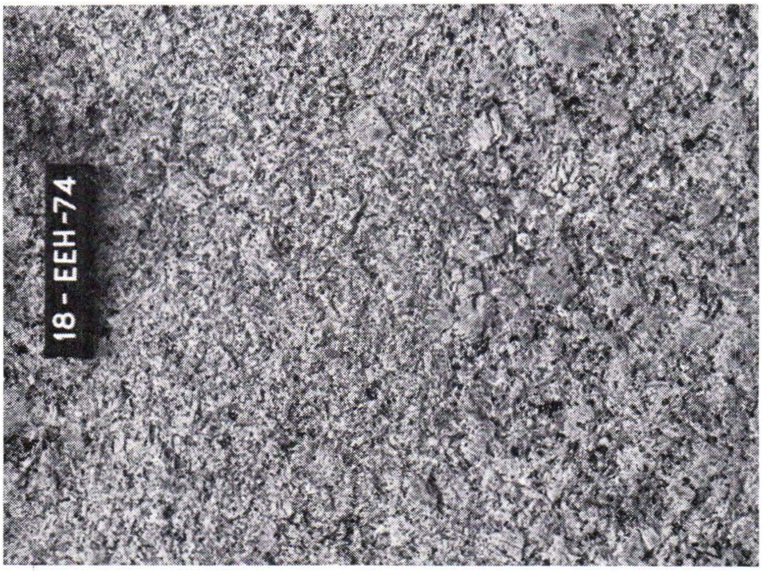


Fig. 22. Contact between Ytö granite, left, and the normal Laitila rapakivi, right. Note the abrupt change in grain size of the biotite and alkali feldspar at the contact. Same locality as in Fig. 21. 1/4.6 natural size. Photo: Erkki Halme.

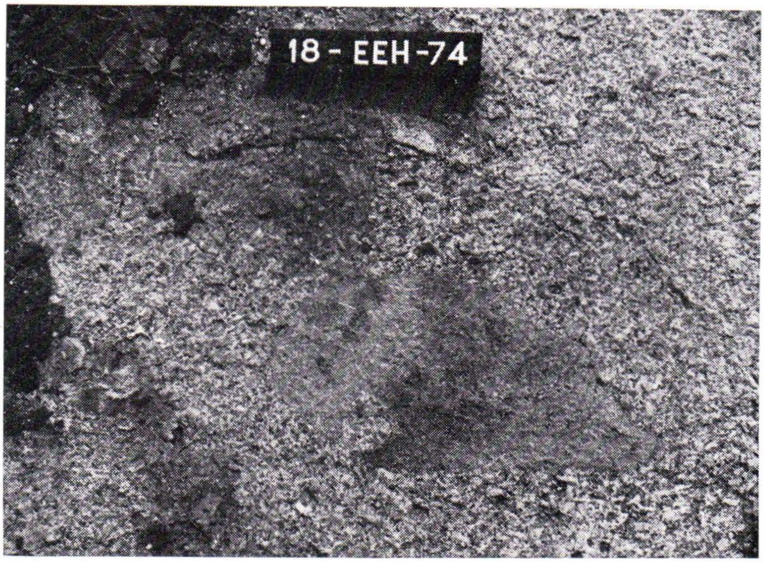


Fig. 23. Autolith in the marginal Ytö granite. Same locality as in Figs. 21 and 22. 1/4.3 natural size. Photo: Erkki Halme.

Fig. 24. Autolith, with alkali feldspar phenocrysts, in the marginal Ytö granite. Sampling site No. 36 in Plate 1. Ytö, Laitila. Photo: Åtso Vorma.

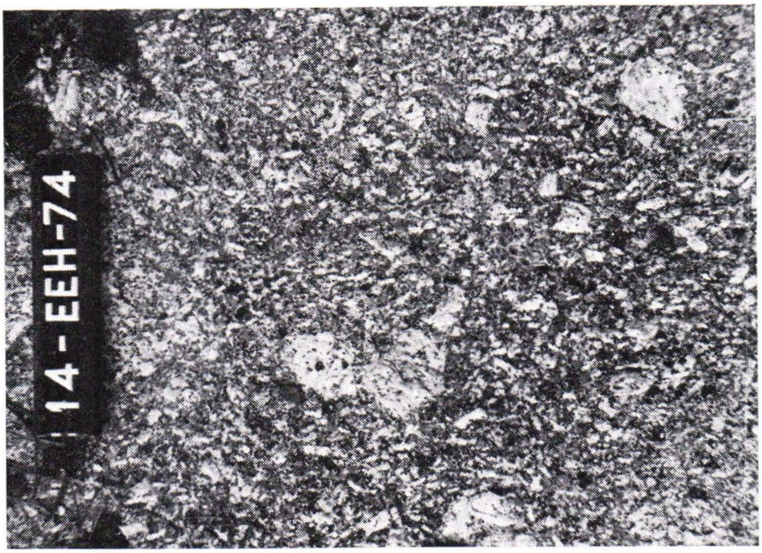


Fig. 25. Typical occurrence of Suutila granite with three generations of alkali feldspar, viz., the megacrysts, the lath-shaped phenocrysts with a marked parallel arrangement, and the ground-mass alkali feldspar. Northern part of the Suutila—Katinhäntä complex. Two km northwest of sampling site No. 38 in Plate 1. 1/3.2 natural size. Photo: Erkki Halme.

Fig. 26. Schlieren of Katinhäntä aplite in the Suutila granite from the contact zone between the two rocks. Southeastern part of the Suutila—Katinhäntä complex. 250 m west of sampling site No. 40 in Plate 1. Karjalankylä, Karjala. 1/4.3 natural size. Photo: Erkki Halme.

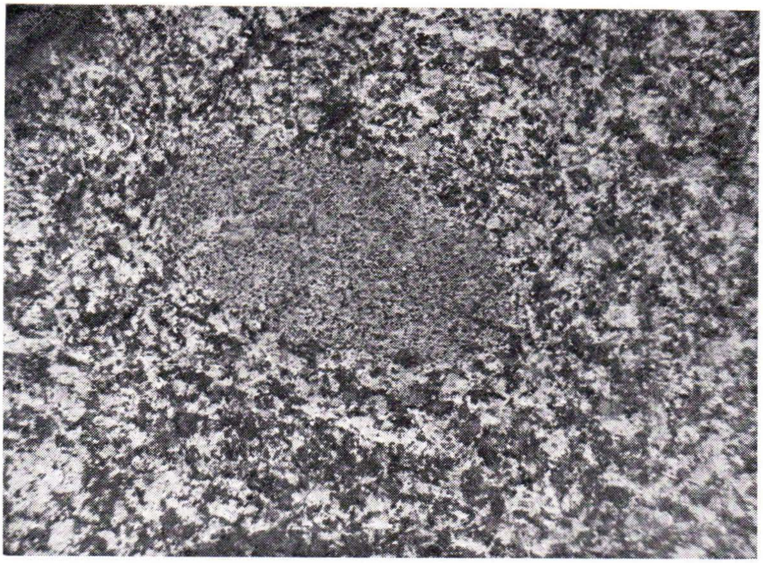


Fig. 27. Typical occurrence of Katinhäntä aplite-type autolith in Suutila granite. Eastern part of the Suutila—Katinhäntä complex. Between sampling sites Nos. 38 and 40 in Plate 1. Suutila, Karjala. 1/2.0 natural size. Photo: Erkki Halme.

Fig. 28. Fine-grained aplitic autoliths with alkali feldspar phenocrysts in Suutila granite. Southeastern part of the Suutila—Katinhäntä complex. Near sampling site No. 39 in Plate 1. Suutila, Karjala. 1/4.0 natural size. Photo: Erkki Halme.

their mutual contacts found and the ring structure of the body demonstrated. In the Ytö granite, the nature of the contact between the central and marginal facies is not clear; so far no abrupt contact line has been found. By analogy with the Katinhäntä—Suutila body, the two varieties of Ytö granite should be expected to show a sharp contact between them.

The contacts of Ytö granite against the normal Laitila rapakivi are exposed in a few localities and its younger age can be demonstrated. So far, the contact between the Suutila granite and normal rapakivi has not been exposed. The contact relations are evidently identical to those between the Ytö granite and normal rapakivi, i.e., the Suutila granite can be taken to be younger than the normal Laitila rapakivi. The contacts between the marginal Suutila granite and the central Katinhäntä aplite, however, are to be seen in many places. As a whole, the contacts are very confusing. The contact surface seems to be very gentle, dipping outward from the Katinhäntä aplite. Actually, there is a contact zone with interpenetrative contacts (Fig. 26) where the are relations cannot be determined. In this contact zone, in many places the tops of the small hills are of Suutila granite, the roots of Katinhäntä aplite; the central granite (aplite) dips gently under the marginal Suutila granite. To this picture also belong the fine-grained autoliths in the Suutila granite. Many of the autoliths bear a close resemblance to the Katinhäntä aplite (Fig. 27), some are of a rock finer in grain (Fig. 28). The Katinhäntä aplite proper lacks such autolites.

All these features can be explained if we simply assume the normal rapakivi to have cooled down before the emplacement of the magma that produced the Katinhäntä aplite and Suutila granite. As in the Ytö granite, also here underground cauldron subsidence is the likely mechanism of intrusion. During the first subsidence of the central block, the magma chilled as aplite against the cool walls of the magma conduits and magma chamber. During and after this first intrusion, the temperature of the country rock rose. When the central block subsided anew, new magma rose from the reservoir and filled the potential void between the country rock and the subsiding block. The magma now crystallized slowly because of the higher temperature of the country rock and produced the coarse-grained marginal rim, which composes the Suutila granite. During the rise of this new magma from the reservoir, it brecciated the walls of the magma conduit, which was coated by chilled aplite, and also the margins of Katinhäntä aplite, into fragments, transported and worked up the fragments into the oval autoliths that so frequently are to be found in the Suutila granite.

The central part of the Katinhäntä aplite (chemical analysis No. 41) is an exceedingly homogeneous rock, where only occasionally alkali feldspar phenocrysts, measuring from one to two cm in diameter, are seen. As one approaches the contact area, the alkali feldspar phenocrysts can be observed to increase; in many places, they occur there at distances of 10—20 cm apart. The largest of the phenocrysts there measure up to 7 cm in diameter. Many of the large phenocrysts are subangular, a few ovoidal, in shape.

The Suutila granite contains in its medium-grained matrix an abundance of lath-shaped, white alkali feldspar crystals. In most places, the size of the laths is such as to give the rock a porphyritic texture (from 1½ × 2 cm up to 4 × 5 cm in diameter, some 50—80 per sq.m.). Often the laths have a parallel alignment, giving a trachytoidal texture to the rock. There is a scattering of large ovoids of alkali feldspar, which measure up to 6 cm in diameter. Chemical analyses Nos. 37 and 38 are from such a typical Suutila granite.

Autoliths in the Suutila granite (Figs. 27 and 28) are similar to those in the Ytö granite. They are mostly oval, even though also some specimens of quite an irregular shape have been found. They measure from a few centimeters to several decimeters in size. Often alkali feldspar phenocrysts, similar both in size and form to those present in the Suutila granite, are found in them (Fig. 28). Two of the autoliths were chemically analyzed (see Nos. 39 and 40). Autolith analysis No. 39 is from the same outcrop as the Suutila granite analysis No. 37.

The Eurajoki complex

At the northwestern margin of the Laitila massif, there is a satellite rapakivi body, the so-called Eurajoki complex. It consists of a marginal hornblende rapakivi, called Tarkki granite, and a central biotite granite, called Väkkärä granite. Since this complex has been recently studied and described briefly by Haapala and Ojanperä (1972) as well as by Haapala (1974) and a detailed description of it will be published in a near future in this series by Haapala, it will be dealt with here only in passing.

Tarkki granite is an even-, medium-grained hornblende rapakivi of a reddish-brown colour. Its mineralogical composition can be seen in Table 9. Both of the chemical analyses in Appendix 2, Nos. 1 and 2, are from the literature.

The age relation between Tarkki granite and normal Laitila rapakivi is not known to the author. The contacts between the Tarkki granite and the central Väkkärä granite show the Väkkärä granite to be younger than the Tarkki granite (Haapala and Ojanperä 1972). The Väkkärä granite was divided by Haapala (1974) into many distinct textural varieties, of which representatives have been analyzed chemically (Appendix 2, Nos. 42—48). Characteristic of the Väkkärä granite is that it is a topaz-bearing biotite rapakivi, in which albite occurs instead of oligoclase-andesine, a characteristic component of other rapakivis. The characteristic accessory minerals, according to Haapala (1974), include zircon, fluorite, monazite, xenotime, opaques, apatite and bastnaesite. How these minerals are distributed among the different varieties is described by Haapala (1974). Also the opaque minerals of the Väkkärä granite have been studied by him in detail. Haapala has shown that Väkkärä granite possesses many of the characteristics of so-called tin granites; cassiterite and columbite, for example, characterize the porphyritic and coarse-grained types of Väkkärä granite.

Dike rocks

The Laitila massif and its country rocks are cut by different kinds of rapakivitic dike rocks. In addition to the dikes referred to in Table 9, quartz dikes have also been observed. In the following, only those dikes are described of which a chemical analysis is available.

Analysis No. 49 is of a light-coloured, reddish, medium-grained biotite rapakivi, surrounded by normal Laitila rapakivi. Owing to the poorly exposed contacts, the direction and the width of the dike remain undetermined.

Analysis No. 50, published by Hietanen, is of a medium-grained rapakivi dike cutting the trondhjemitic country rock of the Laitila massif, about two km outside the southwestern contact. The mineral composition, according to Hietanen, is quartz, alkali feldspar, plagioclase, biotite and magnetite.

Analysis No. 51 is of a rapakivi granite porphyry dike, more than 10 meters in width, trending N30E and cutting the normal Laitila rapakivi in the southeastern part of the massif. In a small-grained to medium-grained reddish matrix, there are red alkali feldspar phenocrysts, varying from 1 to 2 cm in diameter, in places up to 4 cm. The largest of the phenocrysts are ovoidal in shape, the smaller ones angular. The rock has a mineral composition typical of biotite rapakivi. The accessory fluorite, zircon, apatite and opaques characterize the rock.

Quartz porphyry dikes have been met with only in connection with the Eurajoki complex, where a set of subparallel dikes cut the Tarkki granite (Haapala and Ojanperä 1972). The chemically analyzed quartz porphyry (No. 52) contains, according to Haapala (personal communication), in an aphanitic groundmass of alkali feldspar, quartz, plagioclase, biotite, chlorite, topaz and accessories phenocrysts of alkali feldspar, quartz, plagioclase and topaz.

Chemical composition of the Laitila massif

Introductory notes

A list of chemically analyzed rock samples from the Laitila massif is given in Appendix 1. These samples were described in the previous chapter, where certain rapakivi samples were grouped together. While this classification will be used in the following graphical illustrations of the results, a summary of the grouping is necessary. Analyses Nos. 1 and 2 both apply to the Tarkki granite (the hornblende granite of the Eurajoki complex), and Nos. 3—16 to the group consisting of normal Laitila rapakivi, even though this includes some granite porphyritic varieties and even-grained contact varieties; Nos. 17—32 form the group of various, mostly even-grained biotite rapakivis (which also includes the even-grained hornblende-bearing biotite rapakivis Nos. 25 and 26); Nos. 33—41 constitute the group of Ytö granite and related rocks, and Nos. 42—48 the Väkkärä granite group (the central granite of the Eurajoki complex), while Nos. 49—52 all represent rapakivitic dike rocks.

The 52 silicate analyses and the mean calculated from them are given in Appendix 2. The Niggli values and the CIPW norms of the 52 analyses and of their mean are given in Appendix 3. For each analysis, the Niggli values and the norm have been calculated, in column *a*, by excluding, and in column *b*, by including F, CO_2, Li_2O, Rb_2O, SrO, BaO and ZrO_2. This is because in many of the analyses these elements have not been determined. This procedure makes all the Niggli values and all the CIPW norms in columns *a* mutually comparable.

In Appendix 3, No. 53, the Niggli values and the CIPW norm are calculated from the mean chemical composition of the Laitila massif, No. 53 of Appendix 2. A more correct way to calculate the mean would have been to calculate it from the individual values, Nos. 1—52 in Appendix 3. For the Niggli values, this procedure has also been followed (see Table 7), leading to a slightly different result from that in Appendix 3, No. 53, column *a*. This procedure is not, however, suitable for norm calculation because this would lead, for instance, to the coexistence of *C* and *wo*, and of *hm* and *fs* in the norm, respectively.

An observation suggesting systematic minor errors in the older chemical analyses is also worth mentioning. A survey of the *a* columns of the CIPW norm table of Appendix 3 reveals that certain of the norms contain the normative *wo* while most of them contain *C*. Most of the old analyses show *wo*, white all the new analyses, with one exception, show *C* in the norm. The reason for this is presumably that in the old analyses calcium was weighed as oxide; the tranformation of oxalate through carbonate into oxide may have been incomplete and the oxide itself was hygroscopic. This seems to be the reason why the old analyses contain *wo* in the norms. Of course, comparable systematic sources of errors may have occurred in the Al_2O_3 determination as well.

Of the samples for which chemical analyses are given in Appendix 2, 38 were also analyzed for REE, Hf, Th and U by the method of instrumental activation analysis. The results appear in Appendix 4.

Harker and Niggli variation diagrams

The Harker diagram, which was prepared on the basis of Appendix 2 and already shown in Fig. 3, and the Niggli diagram, prepared on the basis of Appendix 3, columns *a*, and already shown in Fig. 5, are reproduced in Figs. 29 and 30. The regression curves are the same as in Figs. 3 and 5. In both of the diagrams, the rock groups, as defined in the foregoing, are indicated by boundary lines, except the points of the dike rocks, which are left without any boundary lines.

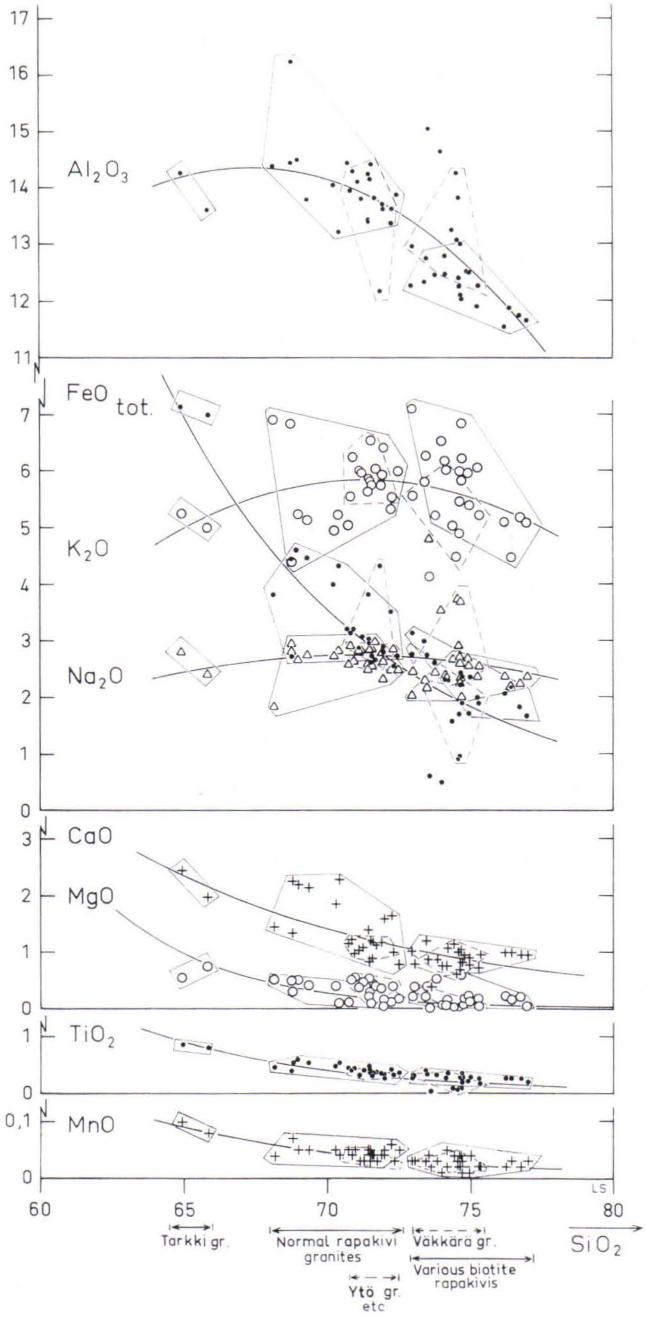


Fig. 29. Harker diagram of the rocks from the Laitila massif. For details, see text.

The diagrams reveal characteristic fields of each granite group. When the normal rapakivi is taken as a standard for comparison with other varieties of rock from the Laitila massif, the different groups can be characterized as follows (see also Table 10):

Table 10.
Characteristic features of chemical composition of different rock groups of the Laitila massif as compared with the composition of normal Laitila rapakivi

Tarkki granite	Lower in Si, F, Rb, Li Higher in Fe, Ca, Mg, Ti, Sr, Zr, Ba
Ytö granite and related rocks	Lower in Ca Slightly lower in Ba, Sr Slightly higher in Rb, F Higher in Mg, Li, Th, U
Various biotite rapakivis	Lower in Ca, Mg, Al, Fe, Ti, Mn, P, Ba Slightly lower in Sr, Hf Slightly higher in Rb, F Higher in Si, Th, U,
Väkkärä granites	Lower in Ca, Fe, Mg, Ti, Mn, Sr, Zr, Ba, P, REE Higher in Si, F, Rb, Li

The composition of the Tarkki granite falls distinctly outside the composition fields of other chemically analyzed rapakivis contained in the massif. The Tarkki granite, being the most basic of the rocks studied, is characterized by higher iron, calcium, magnesium, titanium and manganese contents than the normal rapakivis.

The Ytö granites and its related rocks form small composition fields in both the Harker and Niggli diagrams. Mostly the fields lie completely inside the corresponding fields of normal Laitila rapakivi, coinciding with the more acid members. Certain small characteristic features, however, distinguish them from normal rapakivis. The magnesium content is somewhat higher, and the calcium content lower than in the normal rapakivis with the same acidity. This can be seen in both the Harker and Niggli diagrams (*c* and *mg* fields of the Niggli diagram). The very sparse scattering of analytic points of Ytö granite, its autoliths, Suutila granite, its autoliths and Katinhäntä aplite strongly suggests that all are comagmatic in a very strict sense of the term.

As for the various biotite rapakivis, all are more silicic than the normal rapakivis. In addition, the lower calcium, magnesium, aluminium, iron, titanium and manganese contents distinguish them from the normal Laitila rapakivi. A comparison with the composition fields of Ytö granite and its related rocks, all of which are biotite rapakivis too, shows that their fields are different, mainly owing to the lower silicium content and higher aluminium content of the latter.

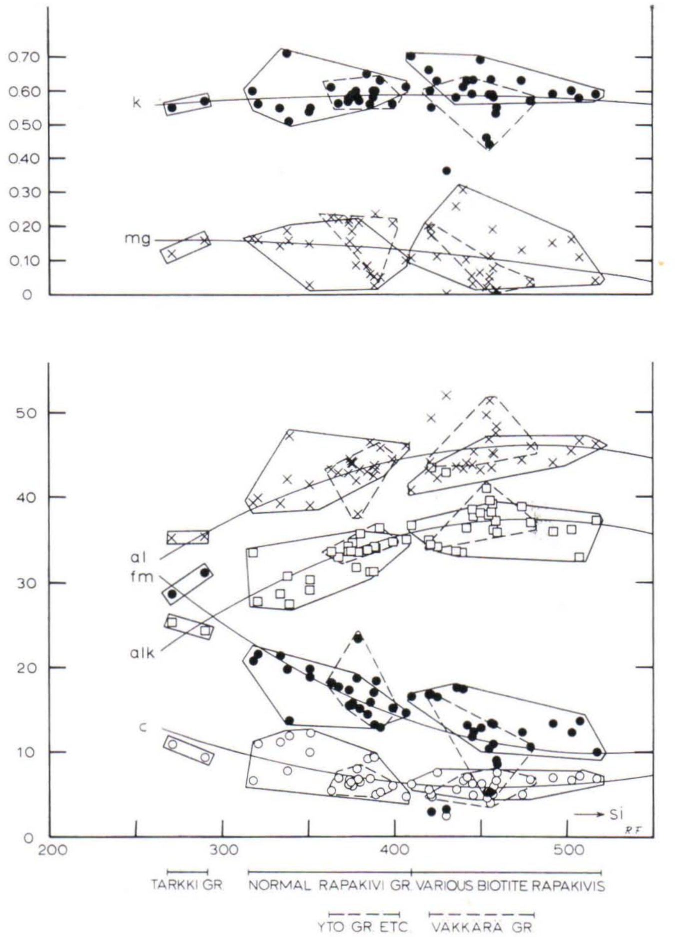


Fig. 30. Niggli diagram of the rocks from the Laitila massif. For details, see text.

The Väkkärä granite, also being a biotite granite, has many features different from those of normal rapakivis and also different from those of the biotite rapakivis discussed in the foregoing. Its silicium content is higher than in the normal rapakivi and approximates that of biotite rapakivis in general. In regard to such elements as calcium, magnesium, iron, titanium and manganese, the Väkkärä granite registers lower figures than the normal rapakivi. The aluminium content is lower than in normal rapakivis but higher (topaz-bearing), on the average, than in the other biotite rapakivis (see Harker diagram). In regard to alkalies, the Väkkärä granites are poorer in potassium and richer in sodium than the other biotite rapakivis. In his study on the geochemical characteristics of rapakivi granite varieties associated with greisen-type mineralization, Haapala (1974) demonstrated that the Vakkärä granite is characterized by low magnesium and iron contents, by exceptionally high fluorine content, and by a combination of relatively high silicium and aluminium contents, when compared with other Finnish rapakivi analyses.

About the normative composition

The norms in Appendix 3 were calculated in two different ways. The norms in the *a* columns are comparable because the F, CO_2, Li_2O, Rb_2O, SrO, BaO and ZrO_2 have been excluded from the calculations. These elements and oxides have been determined in only some of the analyses. The *b* columns were calculated by including all the elements analyzed. Only those *b* columns are comparable with each other that are based on the same analyzed elements. It is true that certain of the elements, even though not analyzed separately, have influence on other analyzed elements and in this way contribute to the norms of the *a* columns. Thus, Ba in the classical silicate analysis is distributed between the sesquioxides, CaO and MgO; Sr follows the CaO, Zr the Al_2O_3, and Rb the K_2O, etc. However, as a whole the influence of these elements on the norms is insignificant. The influence of F (and CO_2) alone causes real concern and hinders the application of the results of experimental petrology to the interpretation of the crystallization of rapakivi.

In many analyses, especially those involving high fluorine, the inclusion of fluorine in the norm calculation would exhaust much of the Ca (to produce normative fluorite), in some analyses all of it, and lower the *an* values. In some of the analyses, the excessive F content has hindered the norm calculation in column *b*: for instance, when extra fluorine is left after all the Ca had been consumed in fluorite. The *b* columns of these analyses have been left blank. These are cases where the rock contains plenty of topaz in addition to fluorite in its mode. This is also the reason why the results of the experimental petrology are applied to the rocks of the Laitila massif cursorily.

In Appendix 3, the normative $Q + or + ab$ have been recalculated as 100 and are indicated as *Qu*, *Or* and *Ab*. In Fig. 31, the *Qu*, *Or* and *Ab* of the *a* columns have been plotted on a triangular diagram. In diagram A, the composition points are indicated along with the area that gives the maximum from the contoured frequency distribution diagram of the normative composition of 571 chemically analyzed plutonic rocks (Tuttle and Bowen 1958). In addition, the isobaric minimum in the haplogranitic system is indicated for H_2O pressures of 500, 1 000, 2 000, 3 000 and 4 000 kg/sq.cm. As seen, with increasing H_2O pressure, the minimum shifts toward the *Ab* corner. On the other hand, with an increasing HF content of the melt, the minimum shifts nearer to the *Or* corner, reducing the potassium feldspar field (v. Platen 1965).

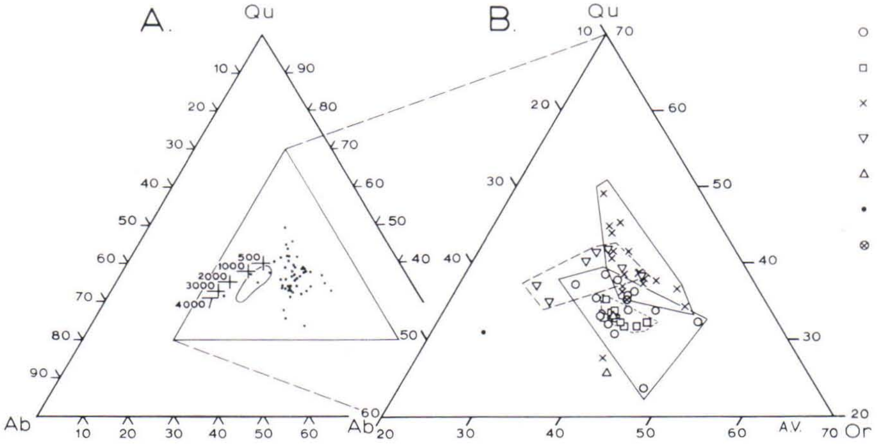


Fig. 31. The normative *Q*, *ab* and *or* of the rocks contained in the Laitila rapakivi massif plotted in a triangular *Qu-Ab-Or* diagram. 1. normal Laitila rapakivi, 2. Ytö granite and related rocks, 3. various biotite rapakivis, 4. Väkkärä granite, 5. Tarkki granite, 6. quartz porphyry dike, 7. granite porphyry dike. For details, see text.

Most of the analytic points lie between the *Or—Qu* side and the minimum indicated in the figure — a feature regarded as characteristic of rapakivis in general by earlier rapakivi researchers.

The introduction of anorthite to this system would shift the minimum melting point toward the *Or—Qu* side as shown by, for instance, James and Hamilton (1969) when using 1 kilobar H_2O vapour pressure. In the haplogranitic system, most of the analytic points of the Laitila rapakivi would lie either in the potassium feldspar field or in the quartz field. If the anorthite content (column *a*, Appendix 3) were included, many of the points would shift into the plagioclase field. If the anorthite content of column *b* were taken into account, many of the analytic points would be shifted back into the potassium feldspar field. These inexactitudes hinder the author from drawing conclusions concerning the crystallization of the rapakivi magma of the Laitila massif.

Diagram B of Fig. 31 indicates the distribution of different rock types in this *Qu—Or—Ab* diagram (see also the contoured diagram of Fig. 8 a). The fields of various biotite rapakivis and the normal rapakivis overlap only partially. The differentiation of the magma from the *Or—Ab* side toward the *Qu* corner is demonstrated by this diagram. The Ytö granite with its related rocks has a very small field, contained entirely inside that of normal rapakivis. The exceedingly small scatter of the Ytö granite points is again an indication of the coherency in chemical composition of this group of rapakivis. The topaz-rich roks — the Väkkärä granite and quartz porphyry, both of the Eurajoki complex — trend toward the *Ab—Qu* side of this diagram.

Trace element composition

P, F, Zr, Sr, Ba, Rb, Li and Ti

To determine the characteristic features of the different rock groups in the light of the trace elements in the analyses of Appendix 2, different kinds of variation diagrams were prepared, certain of which have been presented in Figs. 32—35. A summary of the comparison is given in Table 10. At this point, attention is drawn to Haapala's (1974) observations that the topaz-bearing Väkkärä granite is characterized by, for instance, high contents of Li and Rb, and low contents of Ba, Sr, Ti and Zr, compared with the normal rapakivi granites; all this is in accord with Table 10.

Fig. 32 illustrates the phosphorus plotted against the fluorine. Attention is here drawn to the omission of the composition points of the Väkkärä granite from the diagram, because of its very high fluorine content. The diagram shows that each group of granites has quite a wide range of variation in its fluorine content. The phosphorus content seems to be more characteristic.

The phosphorus content decreases in the following order: Tarkki granite — normal rapakivi/Ytö granite, etc. — various biotite rapakivis/Väkkärä granite. The mean of all the P_2O_5 determinations of the Laitila massif is 0.074 % P_2O_5 (Appendix 2, No. 53). This is less than that of Sahama's standard mixture of east Fennoscandian rapakivi granites, viz., 0.18 (Sahama 1945, p. 44). Fig. 32 shows that also the average P_2O_5 content of the normal Laitila rapakivi, which is the prevailing textural variety of the massif, still is considerably smaller than that in Sahama's standard mixture.

Nos. 43—48 in Appendix 2 show that the fluorine content of Väkkärä granite is really high, from 0.39 to more than one per cent. The other biotite rapakivis show lower values. It is remarkable that the highest fluorine content among the group of various biotite rapakivis, 0.52 % F, occurs in the topaz-bearing, even-grained rapakivi, No. 23, which is similar in appearance to the even-grained Väkkärä granite. Fig. 32 shows also that, on the average, the various biotite rapakivis and Ytö granite with its related rocks have a slightly higher F content than the normal Laitila rapakivi. The available analyses show the mean fluorine content to be 0.38 % (Appendix 2, No. 53), or almost the same as the fluorine content in Sahama's standard mixture (0.36 % F).

All these figures are in agreement with Sahama's observation (Sahama 1945, p. 45) that fluorine is much more abundant in rapakivi granites than in other granitic rocks.

In Fig. 33, ZrO_2 has been plotted against SiO_2. Grossly taken, these oxides have as expected a negative correlation. Remarkable is the paucity of ZrO_2 in Väkkärä granites. All the normal rapakivi granites, except one analysis point, fall on a very small field, indicating a very constant amount of ZrO_2 in the normal rapakivis. The ZrO_2 figure of 0.11 % is from an old analysis, No. 10 in Appendix 2, and is possibly erroneous. The Tarkki granite, being the poorest in SiO_2, is characterized by the

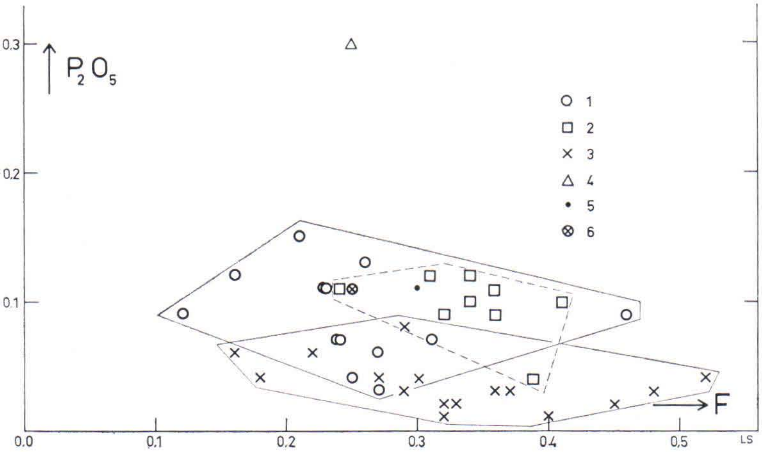


Fig. 32. The F/P_2O_5 diagram of granitic rocks from the Laitila massif. 1. normal Laitila rapakivi, 2. Ytö granite and related rocks, 3. various biotite rapakivis, 4. Tarkki granite, 5. quartz porphyry dike, 6. granite porphyry dike.

highest ZrO_2 figure. The normal Laitila rapakivis, the various biotite rapakivis and the Ytö granite, with its related rocks, have about the same ZrO_2 content, amounting to about 0.04 %. The mean of all the analyses in Appendix 2 gives 0.036 % ZrO_2, i.e., one-third of the ZrO_2 value is Sahama's standard mixture (0.12 % ZrO_2). As zircon is one of the most characteristic accessory minerals in rapakivi granites, this discrepancy is worth examining more thoroughly. Sahama noted and discussed the remarkable difference between his 0.12 % ZrO_2 in the standard mixture and the 0.06 % ZrO_2 in the mean of 10 chemical analyses available to him when he calculated the average of rapakivi analyses (Sahama 1945, p. 36). For the standard mixture, the ZrO_2 was determined, according to Sahama, both in the usual manner in wet chemical analysis and by the X-ray spectrographic method; both methods gave the same result. Understandably, Sahama took this figure to represent the true zirconium content in the standard mixture. Later studies on ZrO_2 contents in, for instance, rocks of the Wiborg rapakivi massif have given lower values. Hoffrén (see Vorma 1971, pp. 8—9) determined the ZrO_2 contents of a dark wiborgite (0.049 %), a normal wiborgite (0.054 %), a pyterlite (0.042 %), two biotite rapakivis (0.045 and 0.050 %) and a porphyry aplite (0.051 %) using the X-ray fluorescence method. By the same method, he received for a topaz-bearing, even-grained rapakivi of Kymi stock, in the Wiborg massif, 0.003 % ZrO_2, and for a porphyritic variety of the same stock 0.022 % ZrO_2 (see Haapala 1974). The volcanic and/or subvolcanic equivalents of Wiborg rapakivi in the Ruoholampi roof pendant, according to the X-ray fluorescence method, have ZrO_2 contents of 0.065, 0.065, 0.071, 0.080, 0.081 and 0.106 % (see Vorma 1975, p. 27). The highest figures are for rocks with a quite low SiO_2 content,

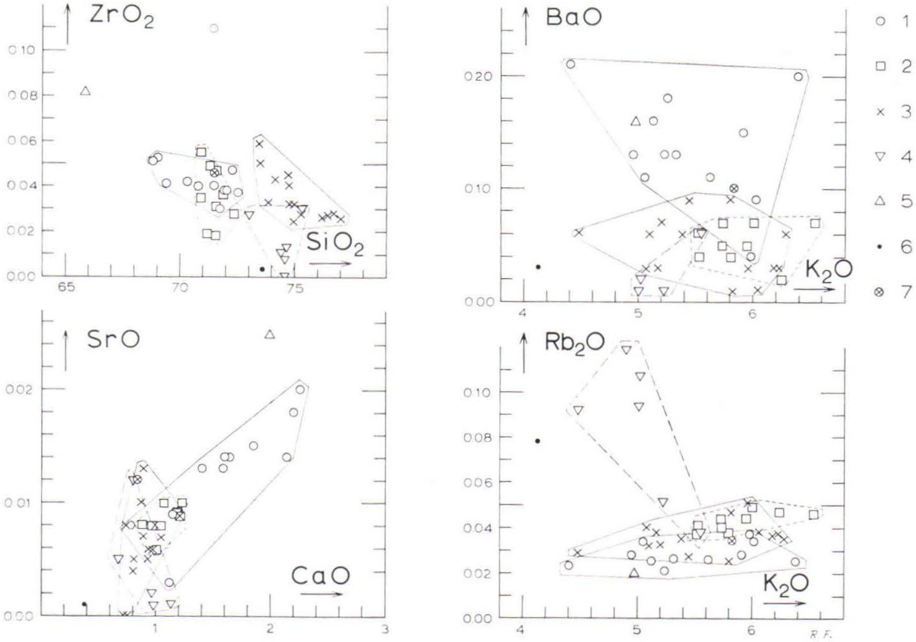


Fig. 33. The SiO_2/ZrO_2, CaO/SrO, K_2O/BaO and K_2O/Rb_2O diagrams of granitic rocks from the Laitila rapakivi massif. 1. normal Laitila rapakivi, 2. Ytö granite and related rocks, 3. various biotite rapakivis, 4. Väkkärä granite, 5. Tarkki granite, 6. quartz porphyry dike, 7. granite porphyry dike.

comparable to that in the Tarkki granite of the Laitila massif. The ZrO_2 content of Sahama's standard mixture cannot be taken, on the basis of the foregoing data, as characteristic of rapakivi granites in general. The characteristic figure for the Laitila massif is about 0.04 %. For the more basic Wiborg massif, it is slightly more, perhaps about 0.05—0.06 %.

In Fig. 33, the dependence of SrO on CaO is also diagrammatically shown. On the average, these oxides have a clear positive correlation. The fields of biotite rapakivis and Väkkärä granites overlap, also that of the Ytö granite overlaps that of various biotite rapakivis. The normal rapakivis have a characteristic field of their own, even though at small CaO values it overlaps the fields of all the other rapakivis. The mean SrO content, 0.0084 %, of the analyses of the Laitila massif (Appendix 2, No. 53) is close to that of Sahama's standard mixture (0.012).

In the same Fig. 33, BaO is plotted against K_2O. Usually barium is regarded as following potassium in the magmatic differentiation and assumed to be enriched together with it in the acid differentiates. As in the Harker and Niggli diagrams no clear change in the K_2O content with increasing SiO_2 can be seen, neither does the BaO/K_2O diagram reveal any positive correlation. In the diagram, the fields of normal rapakivi and biotite rapakivis are clearly separated, as in most of the other diagrams presented. In this diagram, the field of Ytö granite and related rocks overlaps the field of biotite rapakivis, and only touches the field of normal rapakivis. In most of the other diagrams, the field of Ytö granite is inside the field of normal rapakivis. On the average, the normal rapakivis show higher BaO values than the other rapakivis. The mean of all the Laitila rapakivi analyses (Appendix 2, No. 53) is 0.072 % BaO. For normal rapakivi, it is 0.10—0.12 %. In Sahama's standard mixture, it is 0.10 % BaO, i.e., in accordance with the figures for the Laitila massif.

In the same figure, still a fourth diagram is presented, viz., Rb_2O plotted against K_2O. This diagram shows certain interesting features. First, the Väkkärä granite has its own field. Compared with other Laitila rapakivis, it is considerably enriched in Rb_2O. Second, all the other rapakivis, except the quartz porphyry dike, which is related to Väkkärä granite, show small and constant Rb_2O values. The fields of normal rapakivi and biotite rapakivi overlap each other; on the average, the normal rapakivi is slightly poorer than the biotite rapakivi in Rb_2O. The field of Ytö granite and related rocks is now almost completely outside the field of normal rapakivi, but it overlaps the field of biotite rapakivis. The mean Rb_2O content (Appendix 2, No. 53) yielded by the analyses of the Laitila massif is 0.043 %; if the areal distribution of the rocks in the Laitila massif were taken into account, the weighed mean (average) would be slightly less. This figure is by far less than the 0.16 % in Sahama's standard mixture. On the basis of this figure, Sahama (op.cit., p. 50) pointed out that the average content of this element in the acid members of the east Fennoscandian rapakivi series is clearly higher than in granites in general. The figure ($Rb_2O = 0.091$ % or 832 ppm Rb) to which Sahama compared his Rb_2O figure is also clearly too high for granites in general, according to the present view (see p. 80).

As a matter of fact, some new Rb_2O determinations of other rapakivi granites have recently been published. Vorma in 1971, p. 8, reported Rb_2O values for rocks from the Wiborg massif as: dark wiborgite 0.04 (0.017), normal wiborgite 0.04 (0.024), pyterlite 0.04 (0.045) and 0.05, porphyritic rapakivi 0.13, even-grained biotite rapakivi 0.06 (0.045) and 0.06 (0.045), and porphyry aplite 0.06 (0.045) per cent. The figures in parantheses are regarded as better; they worked out with the revised standard (G1) by the method of X-ray fluorescence. The former figures (older) were arrived at by the method of flame photometry. The rapakivitic Ruoholampi porphyries in the Wiborg massif show still lower Rb_2O values. The six determinations range from 0.019 to 0.036 % (Vorma 1975, p. 27). For the topaz-bearing rapakivis in Kymi stock in the Wiborg massif, Haapala (1974) reported Rb_2O values 0.060 and 0.108 %. The Kymi stock in the Wiborg massif is comparable with the Väkkärä granite of the Laitila massif.

Fig. 34 shows the Rb_2O plotted against the Li_2O. It should be noted that the analytic points of the Väkkärä granite and quartz porphyry contained in the Eurajoki complex, which are extremely rich both in Rb_2O and Li_2O, were left out of the diagram. The diagram shows a marked positive correlation between the two elements.

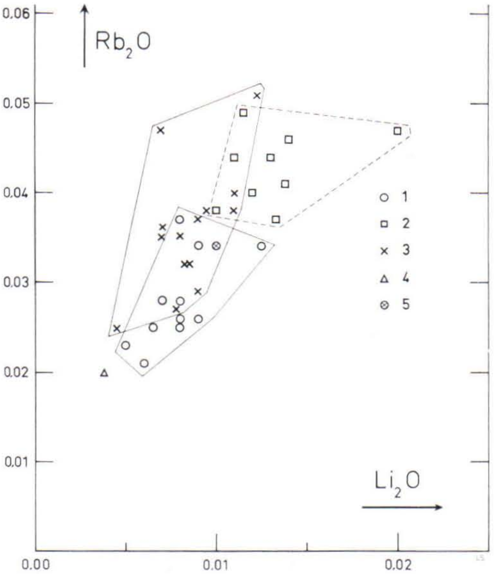


Fig. 34. The Li_2O/Rb_2O diagram of granitic rocks from the Laitila massif. 1. normal Laitila rapakivi, 2. Ytö granite and related rocks, 3. various biotite rapakivis, 4. Tarkki granite, 5. granite porphyry dike. Note that the analyses of Väkkärä granite and quartz porphyry are omitted from this diagram.

This is the only variation diagram in the present paper in which the field of Ytö granite and related rocks lies completely outside the field of normal rapakivi granites; however, it overlaps the field of biotite rapakivis and also the field of Väkkärä granite, which is not drawn in the figure.

The arithmetic mean of the Li_2O values of all the analyses of the Laitila massif is 0.014 % (Appendix 2, No. 53); the contribution of the Li_2O values of the Väkkärä granite to this mean is considerable. The weighed mean, i.e., when the areal distribution of different varieties is taken into consideration, would be somewhat lower. Omitting the Väkkärä granites altogether from the mean, the figure for the other Laitila rapakivis amounts to 0.0094 % Li_2O. Thus the average would be somewhere between these two values. This is twice the figure given by Sahama for the standard mixture (0.0050 % Li_2O).

The recent analyses of rocks of the Wiborg massif show even higher Li_2O values than those given in the foregoing. Vorma, for example (1971, p. 8), reported Li_2O values of 0.02% (dark wiborgite), 0.06% (red wiborgite), 0.04 and 0.02% (pyterlites), 0.04 (porphyritic biotite rapakivi), 0.05 % and 0.01 % (even-grained biotite rapakivis) and 0.03 % (porphyry aplite). On the other hand, the rapakivitic Ruoholampi

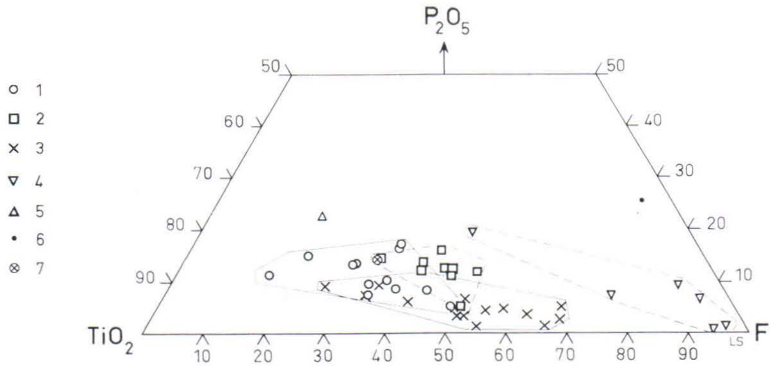


Fig. 35. P_2O_5, TiO_2 and F of the rocks contained in the Laitila massif plotted in a triangular diagram. 1. normal Laitila rapakivi, 2. Ytö granite and related rocks, 3. various biotite rapakivis, 4. Väkkärä granite, 5. Tarkki granite, 6. quartz porphyry dike, 7. granite porphyry dike. For details, see text.

porphyries in the Wiborg massif register Li_2O values comparable to those of Sahama's standard mixture. For six of these rocks, Vorma (1975) reported values from 0.003 to 0.009 % Li_2O. For the topaz-bearing granites of the Kymi stock, Haapala (1974) reported Li_2O contents of 0.02 and 0.04 %.

Besides the foregoing variation diagrams, triangular diagrams were also prepared to show the relative abundance of the several elements. In Fig. 35, the P_2O_5, TiO_2 and F of the analyses in Appendix 2 are plotted. In rapakivis, most of the Ti goes into ilmenite (often replaced by anatase), and most of the P into apatite, in certain varieties also into monazite. All these minerals crystallized at an early stage. Fluorine occurs partly in the hornblende and biotite, and partly (perhaps most of it) in the fluorite, one of the latest minerals in rapakivis. The relative amounts of P_2O_5, TiO_2 and F also therefore indicate to some extent the differentiation grade of the rock. The fields of normal rapakivis, various biotite rapakivis and Ytö granite with related rocks overlap to some extent, while the field of Väkkärä granites lies completely apart. The Tarkki granite and quartz porphyry plot altogether outside any of the fields marked in the diagrams. All the fields marked in Fig. 35 are elongated so as to point to the F corner of the diagram. In the author's view, this indicates a differentiation inside the granite groups. The fields are elongated in most of the other variation diagrams too; in these cases the interpretation is the same.

Hf, Th, U and REE

Sahama's statement (1945) that Hf (0.0028 % HfO_2) is especially enriched in the rapakivi granites and REE, including Y, Sc and Th (totalling up to 0.03 %), comparatively enriched, inspired the author to undertake a study on the distribution of these elements (Y and Sc excluded) in different varieties of Laitila rapakivi. Koljonen and Rosenberg (1974) demonstrated, using the method of instrumental neutron activation, that the REE content of rapakivi is distinct from that of other granitic rocks in Finland. They showed that among the granities in Finland, rapakivi contains more REE than the older rocks and that the light REE are more enriched in them, and that the negative Eu anomaly is more pronounced than in the older granites. All these features they claim to depend on the degree of differentiation the rocks had undergone.

The REE, Hf, Th and U were analyzed from 38 samples (Appendix 4) of the Laitila massif. The samples, and their numbering, are the same as those from which also the standard silicate analyses were performed (Appendices 1—3). The elements were analyzed in the Reactor Laboratory of the Technical Research Centre of Finland in Otaniemi by the method of instrumental neutron activation analysis. The method has been described by Rosenberg and Wiik (1971) and Rosenberg (1972).

Fig. 36 illustrates the Hf plotted against the Zr (see also Appendix 4). The Hf contents vary from less than 5 ppm to 18 ppm with two exceptions, viz. No. 41, the Katinhäntä aplite, which shows an anomalously high Hf content, 37.3 ppm and No. 22, the even-grained biotite rapakivi near Neittamo, which shows a very high Hf content too, viz., 28.6 ppm. Grossly taken, small differencies in the average Hf contents between different groups of rapakivi can be detected. On the average, the more basic varieties — mostly hornblende-bearing —, which also are richer in zircon, show slightly higher Hf contents than the more siliceous biotite rapakivis do.

Most of the Hf/Zr ratios — Appendix 4 and Fig. 36 — are between 0.025 and 0.049. In addition, there are three anomalous figures, viz., those of Nos. 52, 41 and 22. No systematic differences in the Hf/Zr ratios in the different groups of rapakivis can be detected.

The anomalously high Hf content, 37.3 ppm, and the high Hf/Zr ratio, 0.107, are found in the same specimen (No. 41), which also registers anomalously high REE contents and an anomalously high Th content. In regard to Hf, the figures point to cyrtolite, a variety of zircon, which is known to be enriched in Hf in relation to Zr (see, e.g., Fleischer 1955).

The extremely high Hf/Zr ratio, 0.433, was found in the quartz porphyry dike (No. 52) of the Eurajoki complex. The rock is regarded as representing the youngest magmatic phase in the evolution of the Laitila massif. In addition to the anomalously high Hf/Zr ratio, the same specimen is characterized by anomalously low amounts and a different distribution of the REE as compared with other Laitila massif rapakivis. The Hf content of this quartz porphyry is about the same as in most other rapakivi samples of the Laitila massif. The high Hf/Zr ratio is due to the very small Zr content of the sample, viz., 24 ppm Zr. In evaluating the data, the accuracy of the Zr determination must be taken into consideration; in this case, the determination is by emission spectrographic analysis and the probable error is of the magnitude of 10 ppm. Even though the inaccuracy in both the Zr and Hf values

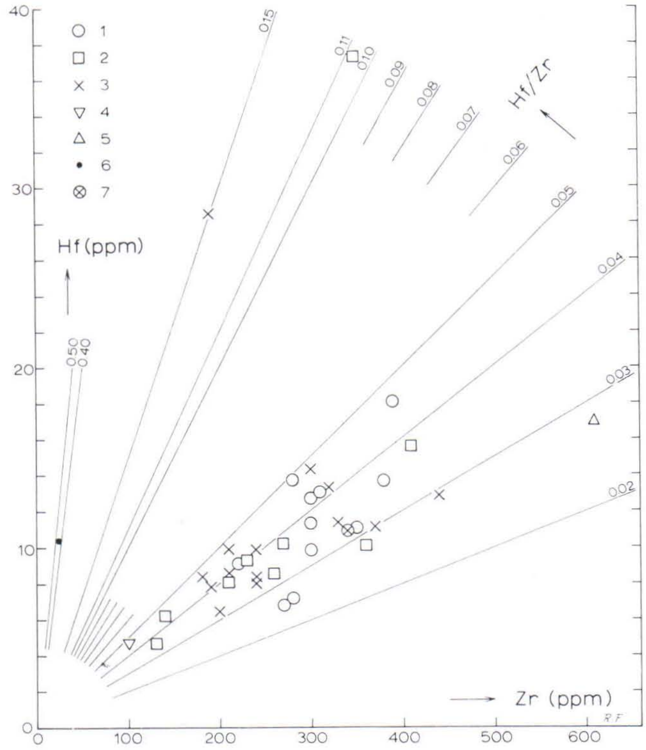


Fig. 36. The dependence of Hf on Zr in the rocks from the Laitila massif. 1. normal Laitila rapakivi, 2. Ytö granite and related rocks, 3. various biotite rapakivis, 4. Väkkärä granite, 5. Tarkki granite, 6. quartz porphyry dike, 7. granite porphyry dike.

were taken into account, the Hf/Zr ratio is much higher than in any other sample from the Laitila massif. This indicates a clear enrichment of Hf in relation to Zr in the last magmatic phase of the massif. As in the case of specimen No. 41, also here the cyrtolite variety of zircon is suggested by the composition.

Sahama (1945) found in his standard mixture of east Fennoscandian rapakivis an Hf content of 24 ppm (converted from HfO_2) and an Hf/Zr ratio of 0.027 (a converted value). As was shown earlier, Sahama's figure for Zr is clearly higher than those found in the present study for rapakivis in general. The Hf/Zr ratio reasonably well fits in with the present study. Thus Sahama's Hf figure also is somewhat higher than those found for rapakivis in general.

It is demonstrated (see, e.g., Hampel 1972, pp. 488—489) that hafnium follows zirconium in geochemical behavior. The Hf/Zr ratio is regarded as remaining practically constant in any process of magmatic fractional crystallization. Departing from this, Gottfried and Waring (1964) and Gottfried at al. (1968) demonstrated that the Hf content and the Hf/Zr ratio in zircon indicate a progressive enrichment of hafnium in relation to zirconium from the mafic to the more siliceous rocks in igneous rock suites.

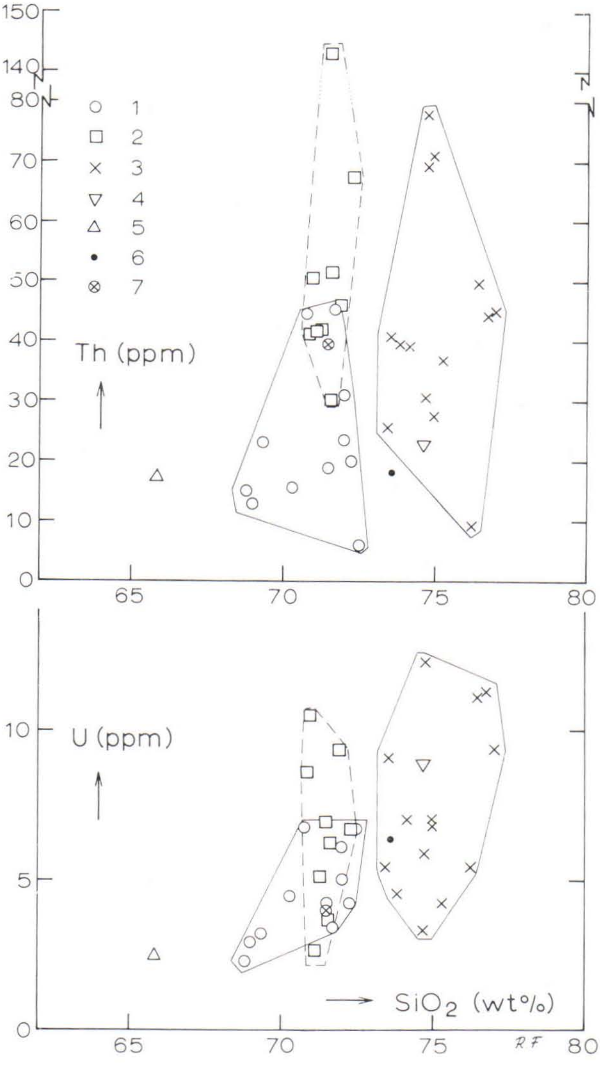


Fig. 37. Variations of Th and U concentrations in rocks from the Laitila massif. 1. normal Laitila rapakivi. 2. Ytö granite and related rocks, 3. various biotite rapakivis, 4. Väkkärä granite, 5. Tarkki granite, 6. quartz porphyry dike, 7. granite porphyry dike.

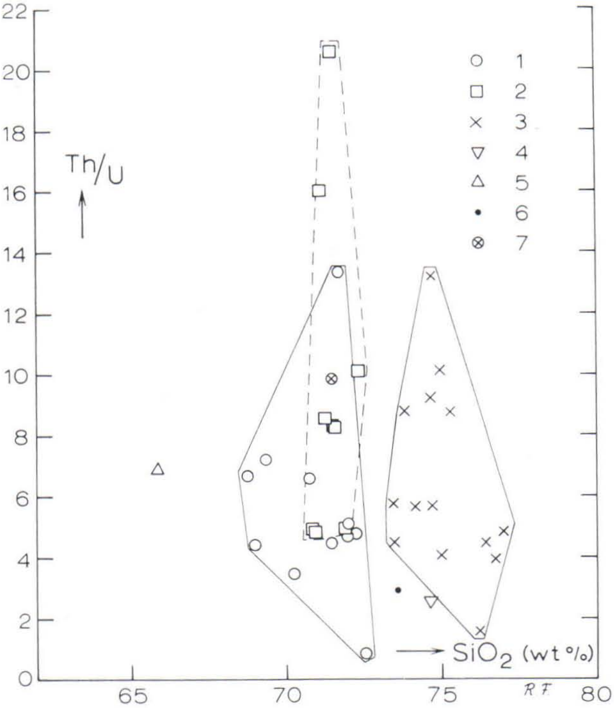


Fig. 38. Th/U ratios in rocks from the Laitila massif. 1. normal Laitila rapakivi, 2. Ytö granite and related rocks, 3. various biotite rapakivis, 4. Väkkärä granite, 5. Tarkki granite, 6. quartz porphyry dike, 7. granite porphyry dike.

The Th and the U of the Laitila samples (Appendix 4) have been plotted against the SiO_2 in Fig. 37. Grossly taken, both the U and the Th show an increment with increasing SiO_2. In the case of the U, the trend of the increment is clear. The Katinhäntä aplite, No. 41 (Appendix 4), registers an anomaously high Th content (143 ppm). This rock, like the Ytö granite and Suutila granite, is characterized by the ubiquitous occurrence of accessory monazite, which occounts for the high Th content. In the author's view, the major part of the Th in the Laitila rapakivi is bound to minerals such as monazite, allanite and apatite (see also Table 9), possibly also thorite. Most of the Th values in the Laitila rocks are between 5.8 and 77.8 ppm. This is in accord with the Th content (35 ppm) in Sahama's standard mixture of east Fennoscandian rapakivi granites (Sahama 1945). The U contents in the samples studied have a quite narrow spread, from 2.26 ppm to 12.3 ppm. The normal Laitila rapakivis show U contents 5 ppm, the biotite rapakivis about 5 to 10 ppm.

Fig. 38 illustrates the Th/U ratios plotted against the SiO_2. No systematic change in the ratio in regard to SiO_2 can be found. Most of the ratios lie between 4 and 6. On the average, the Ytö granite with its (monazite-bearing) related rocks register slightly higher Th/U ratios than the other rapakivis. An anomalously high Th/U ratio is found in the Katinhäntä aplite, No. 41 (Appendix 4). The normal Laitila rapakivi, No. 5, in Appendix 4, registers an anomalously low Th/U ratio, 0.86. The Th content of the rock itself is very low, too. So far, the reason for this is not clear. The distribution of uranium between the accessory minerals in the Laitila massif have not yet been studied, nor any systematic heavy mineral study made. The foregoing data suggest that Th and U do not favour the same accesory minerals; Th is to be found in monazite and allanite (minerals which concentrate the larger rare-earth ions) and in thorite (an accessory mineral found in Väkkärä granite (Haapala 1974) and in the Wiborg rapakivi). The minerals into which the U is concentrated are possibly xenotime and zircon (U^{4+} follows the small rare-earth ions).

As for the REE, the treatment described by Koljonen and Rosenberg (1974) was followed to compensate for the effects of the Oddo-Harkins rule. Koljonen and Rosenberg normalized the REE values against the Leedey L/6 chondrite, using for this chondrite the REE contents reported by Masuda et al. (1973), viz.: La 0.378 ppm, Ce 0.976 ppm, Nd 0.716 ppm, Sm 0.230 ppm, Eu 0.0866 ppm, Gd 0.311 ppm, Dy 0.390 ppm, Er 0.255 ppm, Yb 0.249 ppm and Lu 0.0387 ppm. The values for Pr, Tb, Ho and Tm, which were not given by Masuda et al., were extrapolated by Koljonen and Rosenberg (op.cit.) from the smooth curve, plotting the ratio against the average composition in chondrites. The values thus derived were: Pr 0.138 ppm, Tb 0.0568 ppm, Ho 0.0868 ppm and Tm 0.0399 ppm. The normalized REE contents of the samples from the Laitila massif are presented in Figs. 39—41. Departing from Koljonen and Rosenberg, the customary logarithmic scale is used instead of the decimal scale. In the diagrams, the normalized REE contents are plotted against the atomic number.

In Figs. 39—41, the numbering of the samples is the same as in Appendices 1—4. Fig. 39, a and b, illustrates the normalized REE distribution in normal Laitila rapakivi. The even-grained contact variety (No. 13) and the transitional variety between normal rapakivi and the Lellainen-type granite (No. 12) are included in these diagrams. Most of the patterns are quite similar, with the same enrichment of the light REE and the pronounced depletion of the Eu. The scatter of points of the heavier REE in more marked. No. 11 in Fig. 39 b is anomalous because it registers considerably higher REE contents than the other rapakivis. The general form of the patterns, however, is identical to those of most normal rapakivis. This sample is of the Kokemäki granite, which is separated by the rift valley of Satakunta from the main Laitila massif. The present author, as stated earlier, regards this granite as belonging genetically together with the Laitila rapakivi. The REE distribution of the rock, even though it is considerably enriched in the REE as compared with

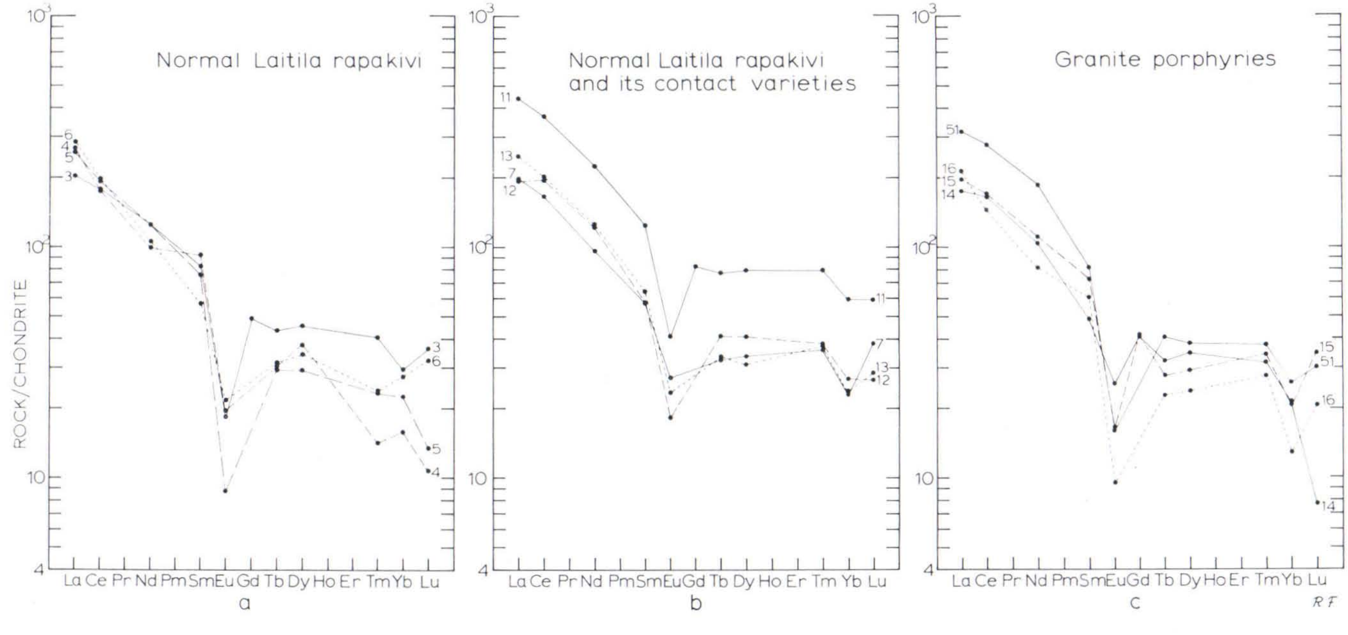


Fig. 39. REE contents of Laitila rapakivi normalized against chondrite (Leedey). The numbers in graphs indicate the analyses in Appendix 4.

a. Normal Laitila rapakivis (Nos. 3—6).

b. Normal Laitila rapakivi (No. 7), Kokemäki granite (No. 11), coarse-grained rapakivi, nearly normal rapakivi (No. 12), and marginal even-grained modification of normal rapakivi (No. 13).

c. Granite porphyries (Nos. 14 and 15), marginal granite porphyry of normal Laitila rapakivi (No. 16), and a granite porphyry dike cutting the normal Laitila rapakivi (No. 51).

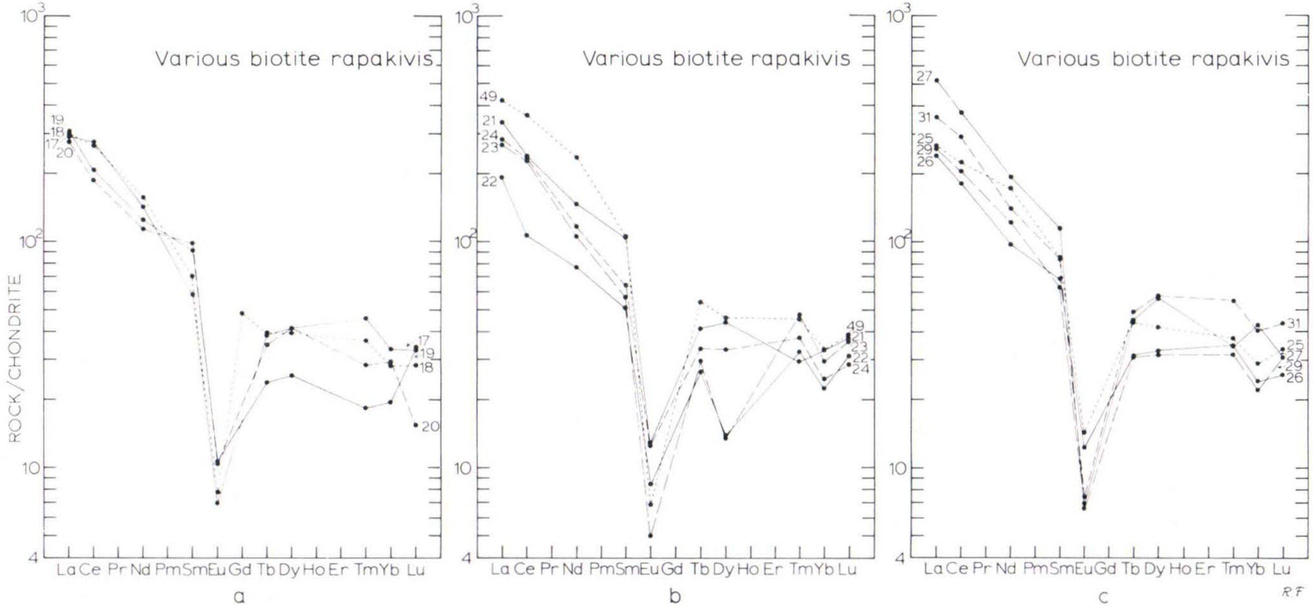


Fig. 40. REE contents of Laitila rapakivi normalized against chondrite (Leedey). The numbers in graphs indicate the analyses in Appendix 4.

a. Lellainen-type even-grained biotite rapakivis (Nos. 17—20).

b. Biotite rapakivi (No. 21), Lellainen-type biotite rapakivis (Nos. 22 and 24), topaz-bearing biotite rapakivi (No. 23), and an even-grained biotite rapakivi dike cutting the normal Laitila rapakivi (No. 49).

c. Spotted granites (Nos. 29 and 31), dark-coloured »auto-intrusion schlieren» in normal Laitila rapakivi (No. 25), coarse-grained biotite rapakivi (No. 26), and porphyry aplite (No. 27).

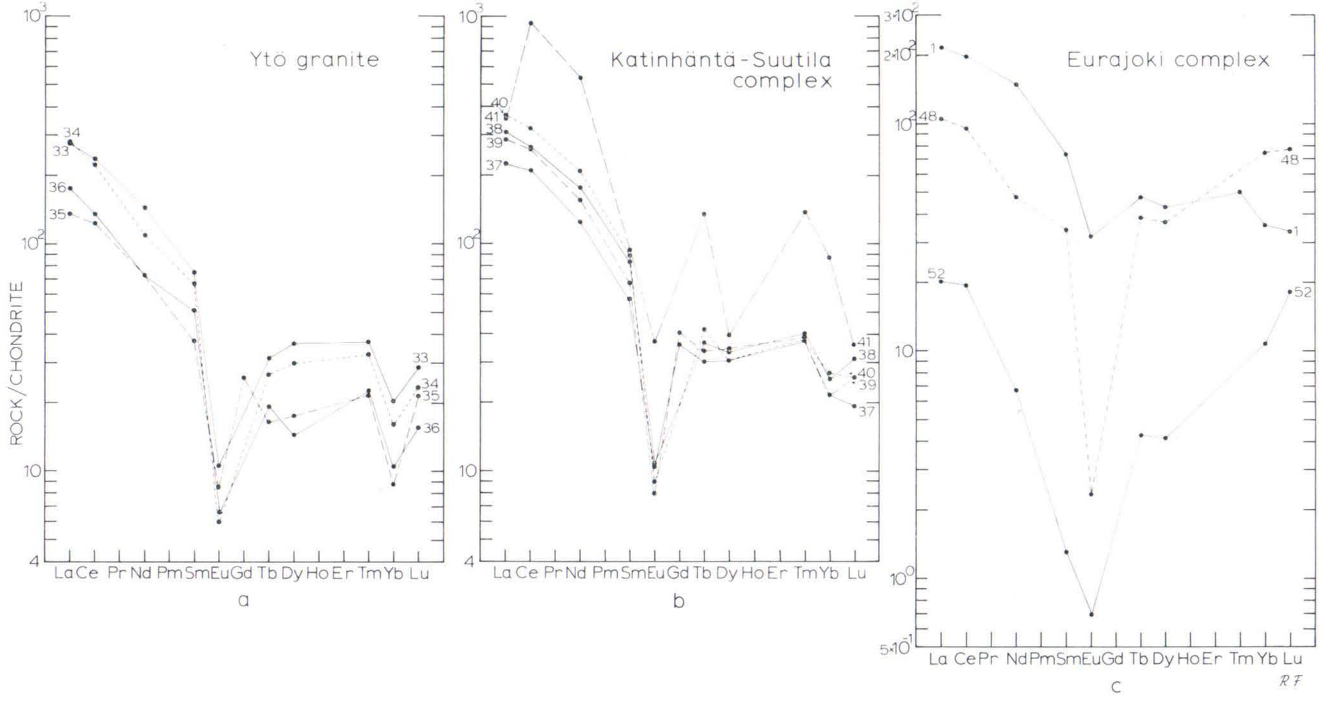


Fig. 41. REE contents of Laitila rapakivi normalized against chondrite (Leedey). The numbers in graphs indicate the analyses in Appendix 4.

a. Ytö granite (Nos. 33 and 34) and autoliths in the Ytö granite (Nos. 35 and 36). Note, samples 33 and 35 are from the same locality.
b. Suutila granite (Nos. 37 and 38), autoliths in the Suutila granite (Nos. 39 and 40), and Katinhäntä aplite (No. 41). Note, samples 37 and 39 are from the same locality.
c. Tarkki granite (No. 1), Väkkärä granite (No. 48), and quartz porphyry dike (No. 52). Note the change of the vertical scale as compared with other diagrams.

other rapakivis, strongly supports the assumption accepted by the author. The other anomalous feature among the normal Laitila rapakivis is the marked depletion of Eu in No. 5 in Fig. 39 a. This is easily understood when the CaO content of the rock (0.78 % CaO, Appendix 2) is taken into consideration. This is far less than in any other normal Laitila rapakivi so far analyzed.

Fig. 39 c includes the data obtained from the granite porphyries. No. 15, the massive granite porphyry of Haukkavuori has an identical REE distribution with those of normal Laitila rapakivi in general (Fig. 39, a and b). No. 16, the granite porphyritic contact varity registers slightly lower REE contents than the normal Laitila rapakivis in general. It is also conspicuously depleted in Eu as compared with most of the rapakivis in Fig. 39, a and b. Appendix 2 shows that in anal. No. 16, the CaO content is the second lowest among the normal Laitila rapakivis. No. 14 is almost identical with those of normal Laitila rapakivis. The REE content suggests that there might be a gradual change from normal rapakivi to this granite porphyritic rock. No. 51 shows a marked enrichment of the lighter REE. This is in accord with the field observation that a dike rock is really in question, a granite porphyry dike cutting the normal Laitila rapakivi. The differentiation in this rock is more advanced and the melt from which it crystallized enriched in the lighter REE.

Fig. 40 assembles the data from various biotite rapakivis. Compared with the patterns for normal rapakivis, the patterns in Fig. 40, show certain differences. First, these rocks are clearly enriched in the lighter REE, and second, the depletion of Eu is more marked. Especially enriched in the lighter REE seem to be the coarse-grained spotted granite, No. 31 (in Fig. 40 c), and the porphyry aplite, No. 27 (in Fig. 40 c), which both are evidently more differentiated than the Lellainen-type biotite rapakivis (Nos. 17—20 in Fig. 40 a, and Nos. 22 and 24 in Fig. 40 b). The coarse-grained Haaro granite, No. 26 in Fig. 40 c, closely resembles in its REE content the normal Laitila rapakivis.

The REE content of the Ytö granite is shown in Fig. 41 a. Nos. 33 and 34 are of the granite, Nos. 35 and 36 of autoliths in the Ytö granite. Both of the Ytö granite samples have almost identical REE contents. The patterns are characterized by the same features as those of most biotite rapakivis. The autoliths in the Ytö granite have patterns almost identical in form to those of Ytö granite. The autoliths, however, are depleted of all the REE as compared with those in the Ytö granite. The almost identical form of the patterns proves, in the author's view, that the autoliths crystallized from the same melt as, later on, the Ytö granite itself.

Fig. 41 b shows the normalized REE contents in the samples from the Katinhäntä—Suutila complex. No. 41, the Katinhäntä aplite, has an extremely high REE content. Even though the CaO content of this rock is only 1.20 % (Appendix 2), its Eu content is as high as 3.20 ppm, suggesting that a considerable amount of the Eu in this rock follows the other REE. This rock also has an unusually high

Th content (143 ppm) compared with the other rapakivis studied, and very high Th/U and Hf/Zr ratios, as already discussed.

The two samples of Suutila granite and two samples of its autoliths are represented in the diagram of Fig. 41 b by patterns Nos. 37 and 38, and 39 and 40, respectively. The forms of the patterns are all highly similar and almost identical to those of Ytö granite (Fig. 41 a, Nos. 33 and 34). In the Suutila granite, no systematic difference can be observed between the REE contents of the granites themselves and their autoliths.

The oldest of the granites of the Eurajoki complex, the Tarkki granite, is represented by one sample, No. 1 in Fig. 41 c. Even though this is the most basic of the rapakivi samples studied, this rock registers REE contents somewhat higher than the normal Laitila rapakivi does. The general form of the pattern is similar to those of normal rapakivis, except that the Eu minimum is not so pronounced as in the latter. No. 48 in Fig. 41 c is of the porphyritic Väkkärä granite, a textural variety of the younger central granite of the Eurajoki complex. Compared with other rapakivis so far discussed, its REE contents and distribution is thoroughly distinct from them. The REE contents are considerably smaller, the depletion of the Eu and the enrichment of the rock in the heavy REE more marked than in other rapakivis (according to Haapala, 1974, the Väkkärä granite is xenotime-bearing, even though it also contains monazite). The Väkkärä granite belongs to the so-called tin granites and it differs geochemically in many respects from other rapakivi granites, as pointed out earlier (see Haapala 1974). No. 52 is from the quartz porphyry dike belonging to the same Eurajoki complex. This pattern has almost the same form as that of Väkkärä granite, indicating a common origin of the rocks. The depletion of the REE is here, however, more advanced than in the Väkkärä granite. To a high degree of probability, the quartz porphyry dike represents the last magmatic activity in connection with the Laitila massif.

In their study on the REE in granitic rocks, Koljonen and Rosenberg (1974, p. 259) claimed that most granophyres, pegmatites and quartz-rich vein rocks contain less REE than the granites do. The concentration of REE often seems to decrease toward the last phases in magmatic differentiation. They also showed that the normalized distribution patterns change in granitic rocks so that in some the heavy REE become enriched. The authors cited claimed that this is possibly due to those REE which did not separate from the magma during the main phase of crystallization. These authors also claimed that in silicic vein rocks, if crystallized under high temperature conditions, the REE may be strongly enriched.

The suggested behavior of REE in magmatic differentiation applied to the Eurajoki complex suggests conditions of higher temperature in connection with Tarkki granite crystallization and lower temperatures in connection with the crystallization of the Väkkärä granite and its quartz porphyry dikes. The granite porphyritic dike rock, represented by pattern No. 51 in Fig. 39 c, and the biotite rapakivi dike, No. 49 in Fig. 40 b, had thus been crystallized at high temperatures.

Comparison with granite composition in general

In the previous pages, attention was paid mainly to the differences in chemical composition between different rapakivi varieties inside the Laitila massif. To ascertain the main differences in chemical composition between the Laitila rapakivi and other granitic roks in general, the mean composition of the Laitila massif (Appendix 2, No. 53) was recalculated to determine the amounts of the various elements, instead of their oxides, in percentages by weight or in parts per million (ppm). These are in Table 11, Hf, Th and U from Appendix 4, column 53, included, compared with the average composition of granitic rocks from the standard tables of Taylor (1964). Vinogradov (1962), Turekian and Wedepohl (1961) and Schroll (1968). In Table 12, the mean REE contents of the Laitila massif are compared with those of Sahama's standard mixture and those of granites in general according to Haskin et al. (1968)

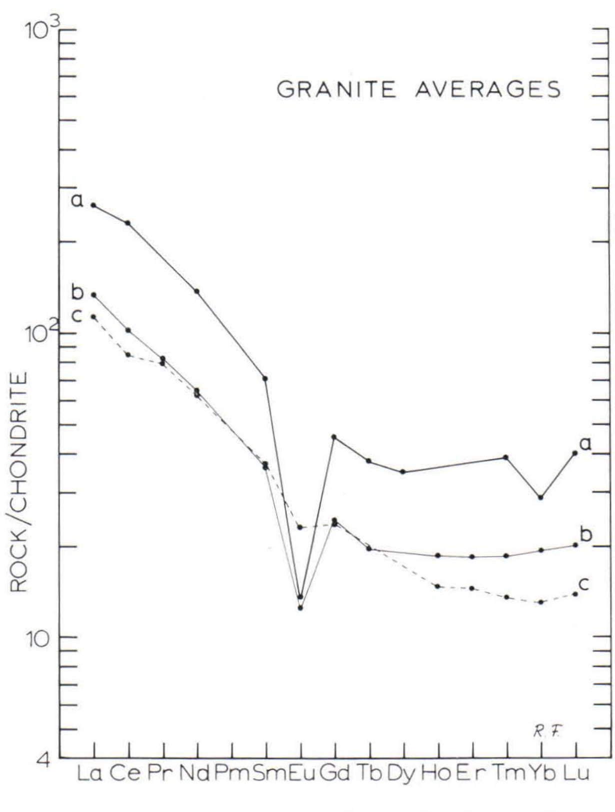


Fig. 42. The REE distribution in Laitila massif, pattern a, compared with those of granites in general (Haskin et al. 1968): granites with more than 70 per cent SiO_2, pattern b, and with 60—70 per cent SiO_2, pattern c.

and Vinogradov (1962). The REE comparison of the Laitila massif in respect of the average composition of granites in general, according to Haskin (op.cit.), is graphically illustrated in Fig. 42. The normalizing of the REE contents in this figure is the same as in Figs. 39—41.

Tables 11 and 12 as well as Fig. 42 revel that most of Sahama's statements (see p. 9) concerning the differences in chemical composition between rapakivis and other granites in general also are valid in regard to the Laitila massif. The tables show that Laitila rapakivi contains somewhat less Al, Mg, Ca and Na than the other granites and more K. In regard to the trace elements, the F, Rb, Zr, Hf, Th, U and REE seem clearly to have been enriched in the Laitila rapakivi and the Li possibly enriched, while it is poor in Sr and P. Some of the figures have changed considerably from those reported by Sahama, but so have also the figures in the composition of granitic rocks with which the comparison is made changed a great deal since Sahama published his extensive study. The only real discrepancy between Sahama's conclusions and those in the present study is in the amount of Li. Sahama's rapakivis were characterized by a dearth of Li; the Laitila massif shows slightly higher amounts of Li than the granitic rocks in general.

Table 11.

Comparison of the mean composition of Laitila rapakivi with the granite averages of Taylor (1964), Vinogradov (1962), Turekian and Wedepohl (1961), and Schroll (1968)

	Mean of Laitila rapakivi	Taylor's granite average	Vinogradov's granite average	Granite averages of Turekian and Wedepohl		Granite averages of Schroll	
				High Calcium	Low Calcium	> 1 % CaO	< 1 % CaO
Si %	33.93	32.30	32.30	31.40	34.70	31.40	34.70
Ti %	0.20	0.23	0.23	0.32	0.12	0.42	0.14
Al %	7.05	7.70	7.70	8.20	7.20	8.20	7.20
Fe %	2.19	2.70	2.70	2.96	1.42	2.96	1.42
Mn ppm .	286	400	600	540	390	450	210
Mg % ...	0.15	0.16	0.56	0.94	0.16	0.94	0.16
Ca %	0.84	1.58	1.58	2.53	0.51	2.53	0.51
Na % ...	1.97	2.77	2.77	2.84	2.58	2.84	2.58
K %	4.67	3.34	3.34	2.52	4.20	2.52	4.20
P ppm ..	322	700	700	920	600	—	—
F ppm ..	3 800	850	800	520	850	—	—
C ppm ..	63	300	300	—	—	—	—
Li ppm ..	65	30	40	24	40	—	—
Rb ppm..	393	150	200	110	170	180	300
Sr ppm ..	71	285	300	440	100	400	100
Ba ppm..	644	600	830	420	840	420	840
Zr ppm..	266	180	200	140	175	190	140
Hf ppm..	11.5	4	1	2.3	3.9	—	—
Th ppm..	38.8	17	18	8.5	17	—	—
U ppm ..	6.14	4.8	3.5	3.0	3.0	—	—
K/Rb	118.8	222.7	167.0	229.1	247.1	140.0	140.0
Ca/Sr	118.3	69.1	52.7	57.5	51.0	63.3	51.0
Hf/Zr ...	0.043	0.022	0.005	0.016	0.022	—	—
Th/U	6.32	3.5	5.1	2.83	5.67	—	—

Table 12.

Comparison of the mean REE contents (in ppm) in Laitila rapakivi with the REE contents of Sahama's (1945) standard mixture, Haskin's et al. (1968) estimates on the average REE contents, and Vinogradov's (1962) granite average

	Mean of Laitila rapakivi	Sahama's standard mixture	Granite averages of Haskin et al.		Vinogradov's granite average
			Granites 60—70 % SiO_2	Granites >70 % SiO_2	
Y	—	40	33.5	42	34
La	100	34	43	50	61
Ce	227	68	83	100	100
Pr	—	15	11.0	11.4	12
Nd	99	51	44	46	46
Pm	—	—	—	—	—
Sm	16.4	11.2	8.5	8.3	9
Eu	1.17	—	2.0	1.10	1.5
Gd	14.2	15.6	7.4	7.6	9
Tb	2.14	3.5	—	1.12	2.5
Dy	13.6	7.0	—	—	6.7
Ho	—	1.75	1.27	1.62	2
Er	—	5.2	3.7	4.7	4
Tm	1.55	—	0.54	0.74	0.3
Yb	7.1	3.5	3.25	4.8	4
Lu	1.17	0.88	0.54	0.78	1
ΣREE[a)] .	> 600	258	249	288	293

a) ΣREE is the total REE content in ppm, including estimates for elements not determined.

DISCUSSION ON THE ORIGIN OF RAPAKIVI MAGMA

Most of the investigators of rapakivi granites regard rapakivis as magmatic rocks. Quite many of them think that the genesis of rapakivi magma is related in one way or other to the genesis of basic magma because of the geographical coexistence of rapakivi granites with basic rocks of the same age.

In the following, only the newest models, which are at the same time the models of greatest importance, representing the origin of rapakivi magma will be reviewed, after which the author will outline the model he thinks best fits the petrochemical peculiarities of rapakivi.

A model representing the origin of the gabbro-anorthosite-syenite-potassic granite suite, rapakivi granite included, has recently been worked out by Barker et al. (1975). According to this model, a mantle-derived, convecting alkali olivine basaltic magma reacts with the K_2O-poor lower crust of the granulite facies to produce magma of quartz syenitic composition. The syenitic liquid in turn reacts with the granodioritic to granitic intermediate crust of amphibolite facies to produce the biotite and biotite-hornblende granites. The process involves both partial melting and the reconstitution and precipitation of refractory phases. Intermediate liquids include MgO-depleted and Na_2O-enriched gabbro, which precipitate, inter alia, anorthosites. The heat source is the basaltic magma; the heat required for partial melting of the roof is supplied largely by the heat of crystallization in the basaltic magma. By this model, based on reaction melting, both the production of rapakivi magma and its emplacement should be anorogenic.

The model of Barker et al. should require positive gravity anomalies over the massifs because the reaction melting produces an accumulation of much olivine and pyroxene in the lower crust. In regard to rapakivi granites, as Barker et al. correctly state, this positive gravity anomaly is atypical. In fact, all the rapakivi massifs in Finland are accompanied by negative gravity anomalies (Honkasalo 1962, Laurén 1970). The proposals of Barker et al. to reconcile this involve the possibility that much of the mafic accumulate produced may have sunk into the mantle, the possibility that the lower regions of these intrusives contain much syenite and anorthosite the densities of which are generally similar to that of the granite found at the surface, and the possibility that the density contrast may increase with depth because of increased proportions of metabasalt and intermediate to mafic intrusives and because of the transition to granulite-facies metamorphic conditions. Barker et al. presume, in addition, that the rapakivi granites were produced in a crust containing much granitic material and propose with this in view the rocks at the present level of exposure (op.cit., p. 156). In such a case, as the present author sees it, it is unlikely that the rapakivis could behave as disharmonious granites, and their trace element petrochemistry could not be easily explained.

Bridgewater et al. (1974), in their atudy on crustal downfolding associated with postorogenic igneous activity in South Greenland, demonstrated that the introduction of a major basic magma mass at a depth melted the lower crustal rocks, and the secondary magmas formed, probably mixed with new mantle material, rose upward along graben-like structures. These secondary magmas spread out at higher levels in the crust and formed norite-rapakivi granite complexes. The massive anorthosites formed by the flotation of plagioclase at the top of sheet-like magma chambers at a depth (for example, a possible mantle—crust interface). In some areas (op.cit., p. 75) as, for instance, the Ukrainian shield, the Baltic shield and Labrador, the anorthosites rose upwards, apparently as semi-solid mushes and reached the present erosion surface at about the same time as the rapakivi suite with which they are associated. In other areas, such as South Greenland and Minnesota, the anorthosites were still forming some 500 m.y. after the formation of the rapakivi suite.

According to this model of Bridgewater et al., the partial melting of the lower crust was due to the basaltic magma. The process itself was described as postorogenic. The present author should call it anorogenic, even though it is postorogenic too, if the temporal relation alone were taken into consideration. If the causal connection with the orogenesis is examined, the process becomes anorogenic in the same sense as the process proposed by Barker et al.

Actually, prior to Bridgewater et al., quite similar ideas on the origin of the anorthosite-mangerite-rapakivi suite were presented by Kranck in 1967 and 1969. He called attention to the identity of the tirilite rapakivi in the Wiborg massif, where also anorthosites occur, with the mangerites associated with the Precambrian anorthosites in Canada and the United States. The mangerites and the associated quartz monzonites there grade locally into granites or syenites. The difference between the rapakivi-anorthosite suite and the anorthosite-mangerite suite was attributed by Kranck to a different level of exposure. In Canada and the United States, the erosion level represents a deeper niveau of the crust than in the Baltic Shield. Kranck assumed (1969, p. 96) that the formation of the parental magma started in the basalt layer of the crust or upper mantle with the formation of olivine basalt magma, which ascended into the lower crust, where it came into contact with gneissic material of rather mafic composition. Partial melting of the latter produced a granitic anatectic melt, which probably had a high potassium-sodium ratio. By mixing this melt and the olivine basalt melt, a basic mangerite or quartz-monzonorite was formed. Where the magmas travelled considerable distances upwards in the crust, crystal settling occurred during the intrusion, and therefore less and less plagioclase and pyroxene that had crystallized early reached upper levels. The melt reaching the surface gave rise to the rapakivi granites. Like other investigators of rapakivitic rocks, Kranck also emphasized strongly the anhydrous nature of these melts.

Ideas similar to those of Barker et al. (1975), Bridgewater et al. (1974), and Kranck (1967 and 1969) on the origin of rapakivi magma had been presented previously by certain Soviet geologists (see Sviridenko 1968, pp. 94—98). Thus Sobolev (1947), studying the rapakivi granites occurring in the Ukrainian Shield, claimed that the rapakivi magma was generated by partial melting of rocks under the influence of heat from a basic magma at high temperature. Velikoslavinskiy (1953), in turn, in connection with his extensive study of the Soviet part of the Wiborg massif, came to the conclusion that the basic (gabbros, anorthosites) to acid (rapakivi) rocks of the rapakivi series formed a magmatic differentiation series. Velikoslavinskij contended that the rapakivi magma was a result of differentiation of basic magma, which by selective assimilation of the country rocks derived its rapakivitic composition. He subsequently (1974) gave up this view of the origin of rapakivi. According to Polkanov (1956), a basic magma, rising into the sial-crust, caused the palingenesis of »ankieutectic» (almost eutectic) granites. Assimilation of this selectively melted material by basic magma produced a hybrid tholeiite magma. Crystallization differentiation of this hybrid magma then produced the rapakivi magma.

Sviridenko (1968), in connection with a study of the Salmi massif in Soviet Karelia, called attention, like Kranck, to the similarity in chemical composition between rapakivi granites and acid charnockitic rocks; Sviridenko took her examples of acid charnockites from Antarctica. In her judgment, the differences in the charnockite suite and the rapakivi suite reflect different depths of emplacement. Sviridenko did not offer any detailed model to represent the origin of the rapakivi magma. She concluded that the magma had been generated at a great depth and that it cannot be a derivative of other magmas, such as, for instance, basic magma. Attention should also be called to the fact that Sviridenko (op.cit., p. 98) thought that the different intrusive phases of rapakivi in the Salmi massif were not all produced by magma from one and the same parent magma chamber.

The foregoing models for the generation of rapakivi are all based on magmatical views. Also metasomatic processes have been proposed to explain the origin of rapakivi. Most of the models based on metasomatism are connected with processes occurring during orogenesis; the rapakivi granites should thus be regarded as post-orogenic but not anorogenic. Among these processes, the one proposed by Sudovikov (1967) merits attention. His model contains both transformistic aspects and anatectic aspects.

In the process of formation of rapakivi granites, Sudovikov distinguished the following stages. First, there took place the stage of transformation of the parent rock (paragneisses) into porphyroblastic granitoids and porphyroblastic gneisses under conditions of deep-seated regional metamorphism and granitization. Then, the stage of rheomorphism, i.e., the rise of »rapakivized» masses to higher levels of the crust, representing the second stage, was characterized by a selective fusion of the porphyroblastic rocks. Sudovikov regarded the chief cause of their »intrusion» to have been the tectonic rise of large blocks of the earth's crust. This took place during the late orogenic period. The last stage in the formation of the rapakivi was the stabilization of the rock, i.e., the magmatic crystallization of the melted part of the mass.

Sudovikov concluded that the alkali feldspar ovoids and quartz contained in them represent the early stage of metasomatic crystallization, whereas the minerals of the groundmass and the plagioclase mantles around the alkali feldspar ovoids are essentially the result of crystallization from the melt formed during the selective fusion of the porphyroblastic rock during the stage of rheomorphism.

Inspired by the foregoing thoughts, the present author tried to develop a model for the origin of rapakivi magma, a model that would bear many features corresponding to those just described but also deviating from them in some respects. The author tried to develop a model that could produce a granitic magma richer in K, F, Li, Rb, Zr, Hf, REE, Th and U, and poorer in Ti, Al, Fe, Mn, Mg, Ca, Na, P, and Sr, than granitic rocks in general, and, in addition, would be characterized by low Mg/Fe and K/Rb and high Ca/Sr ratios. For this, certain characteristic features of the mode of occurrence of rapakivi must first be dealt with.

The rapakivi granites are typical representatives of Walton's (1955) disharmonious granites and of Buddington's (1959) epizonal granites. They emplaced into already cratonized roots of the Svecokarelidic orogenic belt; during the time of emplacement, the denudation and isostatic uplift of the belt was far advanced. The rapakivi magmas thus rose close to the earth's surface; in places, there are evidences of volcanic counterparts of rapakivis (see, e.g., Vorma 1975). This is an indication that in the PT coordination, the slope of the liquidus PT curve was positive and the granitic magma itself poor in H_2O (undersaturated in respect of water). In volatile-rich granitic melts (saturated by water) the slope is negative and magmas of that kind cannot rise close to the surface of the earth (see, e.g., Cann 1970). These magmas cannot rise much upward from the places where they were generated. Magmas undersaturated by water are warmer and generated at greater depths than the hydrous magmas. This line of thought leads to the conclusion that rapakivi magmas are generated deeper in the crust and at higher temperatures than the potassium-rich, Svecokarelidic late orogenic granites.

Another aspect of importance is that in Finland the by geochronologically followable time-axis is about 3000 m.y. long. The major occurrences of granitic rocks are restricted in time to that of the Svecokarelidic orogeny (2200—1800 m.y.). In southern Finland, where Sederholm (1925 b) established his well-known granite division into four groups, the Pb—U ages on zircon for Sederholm's II, III and IV groups of granites are ca. 1900, 1800 and 1700 m.y., respectively (the I group is of synorogenic granodioritic rocks and is here excluded). I.e., all of these are, grossly taken, synchronous with the orogeny. Evidently, there is no granitic magmatism younger than about 1600 m.y. In Sweden, it is true, younger ages are reported, but these have been determined by the method of Rb/Sr.

An observation also of importance is that all these granites occur geographically in the same parts of the Svecokarelidic orogenic belt.

It is noteworthy, further, that Sederholm's II, III and IV groups of granites are mostly really granitic in composition — that is, grossly taken, they are similar in composition.

The foregoing observations suggest the improbability that three entirely different and independent processes would almost simultaneously act to produce three granitic magmas having a similar, though not identical, chemical composition and, further, occurring geographically in almost the same regions. On the contrary, it is highly probable that these three groups of granites were produced by one and the same process, which acted for a very long time and created granitic magmas (and/or migmas) simultaneously at different levels of the crust (compare Härme 1965, p. 36):

- During the culmination stage of the orogeny, when the isotherms ($\sim$700°C) rose up in the crust, at a depth of 10—15 km, an anatectic melt, saturated by water, was generated. This melt was not able to rise upward in the crust. It was this anatectic melt that produced the migmatitic potassium granites in southern Finland (granites of Sederholm's II group).
- In the lower parts of the continental crust, drier conditions and higher temperatures (up to 800—900°C) prevailed during the culmination stage of the orogeny. From regionally metamorphosed rocks — both ortho- and paragneisses — an anatectic granitic melt, which in respect of water was undersaturated, was generated there. However, so long as the compressional

> stage of the orogeny continued, there were only very limited possibilities for this melt to form larger coherent magma reservoirs and to rise gravitatively up through the crust. During the final orogenic stages, when the compressional stage changed into a distensional stage — at this stage the denudation and isostatic uplift of the belt was about 10 km —, the mantle-derived basaltic magma erupted through the crust and formed the Subjotnian plateau basalts whose magma conduits are now indicated by the diabase dike swarms occurring in, for example, southern Finland (see Laitakari 1969). Simultaneously, the water-poor granitic melt, which was generated at the lower part of the crust during the culmination of the orogeny, collected to form larger homogeneous magma reservoirs in the potential voids generated when the compressional stage turned distensional. Probably, at that stage, the whole lower part of the crust contained dispersed granite liquids. Possibly the composition of this »pore magma» was different at different levels of the lower crust (wiborgite magma and pyterlite magma?). At this stage, also the gravimetric diapiric rise of the magma began. A possible emplacement mechanism is very elegantly discussed in a recent paper of Bridgewater and al. (1974). The present author does not enter that field at all but thinks their interpretation is correct.

If the foregoing general theme can be proved to be correct, the generation of rapakivi magma was an orogenic process and the emplacement of rapakivis a post-orogenic process, not an anorogenic one as described in many studies on rapakivis.

The generation of the granites included in Sederholm's group III could be interpreted as an intermediate stage between the two discussed in the foregoing.

The process itself that produced the superheated, water-deficient rapakivitic magma actually could be that described by Brown and Fyfe (1970). They studied the production of granitic melts during ultrametamophism. Their experiments on the partial fusion of crustal materials containing water only in hydrated phases demonstrated that granitic melts undersaturated by water could be produced at temperatures and pressures in accord with observations on the metamorphic state of migmatitic terrains.

Brown and Fyfe emphasized the role of biotite and hornblende in that they contain most of the water in the high-grade metamorphic rocks. The breakdown of micas (biotite, muscovite, phlogopite) and hornblende provides water for melting while a refractory residue remains. Incongruent melting of these minerals result in the formation not only of a granitic melt but also of aluminium silicates (sillimanite, cordierite, garnet), magnetite and pyroxene. This residue would produce the rocks of granulite facies metamorphism. This would be enriched in such elements as Al, Fe, Mg, Mn, Ti, P, (Ca), etc., while the anatectic melt in turn would be depleted of these elements.

The experiments performed by Brown and Fyfe suggested, among other things, that the *Ab/Or* ratios increase with increasing pressure; that the bulk composition of the quartz-feldspathic host has little influence over early melt compositions, but progressive melting must move the liquids towards the bulk composition; that the normative orthoclase contents are dependent on the hydrated minerals associated with the fusion (high temperature melts from hornblende are granodioritic and plot towards the *Ab-Qu* side of the ternary minimum. Low-temperature muscovite melts are granitic and plot towards the *Or-Qu* side), that an increase in the amount of a hydrate seems to reduce normative quartz as these are low silica phases, and that the mafic content of the liquids is highly sensitive to temperature (for example, low magnesium contents are associated with muscovite melting).

Two of the major conclusions Brown and Fyfe draw from their experiments are that the bulk of melt production in nature is probably coupled with the destruction of biotite and hornblende, and that the temperatures of melt formation lie 100—300°C above the water-saturated, minimum melting temperatures.

The foregoing process, as applied to the generation of rapakivi magma, signifies that the lower part of the crust consists of rocks of intermediate- to high-pressure granulite facies (e.g., pyroxene granulites). The bulk of the rocks of the Svecokarelidic orogenic belt was metamorphosed under the conditions of the low-pressure facies series. Certainly, at deeper levels of the crust, the mineral associations correspond to the intermediate- and even high-pressure facies series. Can these rocks then be interpreted as a refractory residue? No direct answer can be given. If they are, many of the compositional characteristics of rapakivis become self-evident. The elements enriched in the residue are depleted in the melt. Thus the elements Al, Fe, Mg, Mn and Ti show understandably low figures in rapakivitic melts. The high K/Na and Fe/Mg ratios in the rapakivitic melts can be explained, referring to the experiments of Brown and Fyfe, by proper balancing of the amounts of hydrated minerals suchs as muscovite, biotite and hornblende in the rock to be fused. It is also noteworthy that most of the rapakivis are associated with anorthosite masses that in most studies are genetically related to rapakivis. If the anorthosite masses have been generated by early plagioclase accumulation from the rapakivi magma, the process has somewhat reduced the amounts of Ca, Na and Al in the melt.

Examination of the behaviour of certain trace elements during the process outlined in the foregoing gives the following pixture.

Rb is one of the most characteristic trace elements in rapakivi. In the Laitila massif, the average K/Rb ratio is 118.8 (Table 11). Only rarely does the K/Rb ratio for common continental rocks fall outside the limits of 160—300, the average being about 230 (Heier and Billings 1970b). In a general review of the K/Rb ratio, Heier and Billings (op.cit.) stated that the mafic rocks trend towards and beyond the upper limit (300) of this ratio, and that the Rb enrichment resulting in K/Rb ratios of less than 160 occurs in differentiated granites and pegmatites. Further, it has been postulated that in the rocks of the mantle, the K/Rb ratio is high, and in the crustal rocks lower.

According to Heier and Billings, during sedimentation, the Rb is concentrated relative to the K in slates. During regional metamorphism, no systematic variations in the Rb concentrations have been detected until the granulite facies conditions are reached. Relative depletion of the Rb in medium- to high-pressure granulite facies rocks, typical of lower continental crust, has been described. Heier and Billings (op.cit.) pointed out that granulite facies rocks have significantly higher K/Rb ratios than associated amphibolite facies rocks.

The conclusion we can draw from the above discussion is that if the granulite facies rocks are regarded as refractory residue of the lower continental crust and they are depleted of Rb in respect of K, the anatectic melt produced in turn is enriched in Rb in relation to K, just as in rapakivis.

Li is the next element to be dealt with. This element is slightly enriched in the rapakivi as compared with granites in general (Table 11).

In sedimentation, the Li follows the Mg and is enriched in argillaceous sediments (from 17 to 207 ppm Li, according to Heier and Billings 1970a), in clays and shales, as compared with, e.g., sandstones and carbonates (Turekian and Wedepohl 1961, Heier and Billings, op.cit.). The lower continental crust of medium- to high-pressure granulite facies affinities contains according to Heier and Billings (op.cit.) about 10 ppm Li. It is depleted of Li as compared with, e.g., argillaceous sediments. In metamorphic rocks, originally geosynclinal sediments, subjected to anatexis under high pressure and high-temperature conditions (water produced only by the breakdown reaction of hydrated minerals), it is highly likely that Li will become enriched into the granitic melt and the refractory residue, even though rich in Mg, becomes depleted of Li (high to intermediate facies granulite rocks). This would be the reason why Li is slightly enriched in rapakivitic rocks.

In magmatic rocks, Li substitutes for Mg extensively. Because of its single charge, Li forms weaker bonds than Mg and therefore in magmatic rocks is concentrated in the late-forming Mg minerals rather than early ones. This is also in accord with the enrichment of Li in the anatectic melt rather than in the refractory residue.

Fluorine is besides Rb another trace element highly characteristic of rapakivi granites. Table 11 shows its average content in the Laitila rapakivi to be 3 800 ppm, i.e., 4—5 times that in granites in general.

In sedimentary rocks, fluorine is especially liable to become camouflaged in OH-bearing minerals, especially clays and shales (see, e.g., Koritning 1971). In clays, approximately 80 to 90 per cent of fluorine is contained in muscovite, illite and related minerals of the mica group. The behaviour of fluorine during regional metamorphism is only vaguely known. The available data suggest that, compared with shales, the metamorphic rocks have generally lost about half of their fluorine content during metamorphism (Koritning op.cit.). If fluorine-bearing mica minerals break down under dry conditions, it is highly likely that the fluorine moves with other mobile components to the anatectic melt, the refractory residue becoming depleted of F. It can be assumed that under melting when the P_{H_2O} is low, the F/H_2O ratio is higher than under melting, when the P_{H_2O} approaches the $P_{tot.}$. This simple assumption, even though the starting material, except the H_2O content, in them were the same, would adjust the F/H_2O ratio in water-saturated anatectic granitic magmas and in granitites crystallized from these to a lower level than in undersaturated ones. The H_2O, being geochemically a very mobile phase, would have great possibilities with the accompanying fluorine to escape from the crystallizing hydrated granitic magmas. From the dry granitic magmas, crystallizing under the conditions of low confining pressure, no large-scale escape of the mobile phase into the country rocks took place — ash-flow eruptions being the principal way in which the mobile phases escaped from the crystallizing granitic magma. A considerable amount of the fluorine remained in the crystallizing magma, substituted for the OH in the structure of the mica and amphiboles and at a submagmatic temperature produced fluorite. In the present author's view, this is the way fluorine became enriched in the rapakivi granites.

Sr is a trace element of which rapakivi granites are depleted as compared with granites in general (Table 11).

In geochemical behaviour, Sr follows, first of all, Ca (Sr is admitted into the Ca site in Ca-rich minerals) but also in lesser amounts K (Sr is entrapped in the K sites). In calcium-rich rocks, very little coherence of strontium with calcium is found because in these rocks the Sr never approaches saturation. In granitic rocks, a definite coherence between the two elements is seen; the increasing Ca content implies an increasing Sr content (Turekian and Kulp 1956, Wehmiller 1972). The average Ca/Sr ratio of the Laitila rapakivi, 118, is about twice that in granites in general (Table 11). The explanation is difficult because no adequate data are available on the behaviour of Sr (actually the Ca/Sr ratio) during ultrametamorphism. A possible way to produce a low-Sr rapakivi magma is to be found in connection with anorthosite bodies associated with rapakivi granites. If it can be proved that the anorthosite bodies are genetically related to rapakivi and produced by the early accumulation of plagioclase from the rapakivitic melt, it is reasonable to assume, too, that Sr has been enriched with Ca into the anorthosite bodies. These rocks, being extremely rich in Ca, could have depleted the magma, from which the rapakivi proper later crystallized, of its Sr. ¹) With reference to granitic rocks supposed to have crystallized from water-saturated, comparatively cool magmas or to have been produced by large-scale granitization, it is understandable that such an early accumulation of plagioclase leading to the formation of anorthosite bodies cannot take place.

The enrichment of zirconium (and hafnium) in the rapakivi magma is more difficult to explain because of the lack of data on the behaviour of zircon in high-grade metamorphic rocks.

In magmatic rocks, Zr is enriched in granitic rocks as compared with basic and ultrabasic rocks (Turekian and Wedepohl 1961, Vinogradov 1962, Taylor 1964). In rapakivi granites, the amount of zirconium, contrary to the foregoing, clearly decreases with increasing silica (Fig. 33). Thus, it seems unlikely that the variation

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¹) Precipitation of plagioclase in basalts has been proposed to explain the prevention of any marked enrichment of strontium in a fractionating basaltic liquid at very low pressure (Green and Ringwood 1967, p. 178).

in the zirconium content in the Laitila massif is solely due to magmatic differentiation; rather is it a result of the generation of rapakivi magma.

In sedimentation, most of the zirconium is contained in the zircon and it is enriched in both arenaceous and argillageous rocks. In the tables published by Turekian and Wedepohl (op.cit.), the Zr content in shales and sandstones is 160 and 220 ppm, respectively. During metamorphic processes, zirconium is highly resistant. During anatexis, Zr is regarded as a femaphile element (see, e.g., Schroll 1966, pp. 331—332), i.e., it is enriched in the restite. The average Zr content in granites (Table 11), however, is of the same magnitude as in sedimentary rocks. This means that there are conditions under which Zr (+Hf) during anatexis moves into the granitic melt. The process producing the rapakivi melt is thought to take place at 100—200°C higher temperatures than the process producing water-saturated granitic magmas. It is known that under granulite facies metamorphism, zircon, at least to some extent, becomes mobile. Not only geochronological regeneration by diffusion takes place in it but also new water-clear zircon crystals crystallize in the rock (see, e.g., Bibikova et al. 1973). This is a reference to the fact that under granulite facies conditions, the mobility of zirconium increases in relation to that under amphibolite facies conditions. The slight enrichment of zirconium in the Laitila rapakivi (266 ppm) in relation to other granitic rocks may be a result of this.

In regard to the Laitila massif, as the author sees it, the magmas poorest in SiO_2 and richest in Zr(+ Hf) are generated at slightly higher temperatures than the magmas richer in SiO_2 and depleted of Zr. During the evolution of the rapakivi suite, perhaps, primary differences in magma composition played a more dominant role than the subsequent differentiation processes during the emplacement and crystallization of the rapakivi.

The comparatively high contents of the Th and U in rapakivi granites also are understandable if the rapakivi melt is produced in the way just outlined. Lambért and Heier (1967) and Heier (1973) studied the vertical distribution of uranium, thorium and potassium in the continental crust. They demonstrated that the acid to intermediate pyroxene-granulite subfacies rocks are depleted of U and Th by factors of about 5 and 9, respectively, when compared with common surface rocks of similar bulk chemical composition. They interpreted the variation in chemical composition with depth in the crust as a result of the differences in mobility of the elements during normal geological processes such as metamorphism, partial melting and upward movement of granitic material and vapour. The loss of U does not run strictly parallel to the Th; but in the case of both of these elements, the major depletion occurs suddenly under pyroxene granulite facies conditions. Thus, if the rapakivi magma is generated under the conditions of intermediate to high-pressure granulite facies metamorphism, the enrichment of U and Th becomes self-evident.

In regard to REE, the rapakivi granites as shown are enriched in them as compared with granites in general. Also the light REE are enriched compared with the heavy ones and the Eu anomaly is pronounced.

At present, a few REE analyses on metamorphic rocks are available. Koljonen and Rosenberg (1974, p. 260) claim that, during early phases of metamorphism, the change in REE contents is small. When the rock reaches anatectic conditions, the REE begin to migrate with silica and alkalis. In rapakivis, most of the REE are probably contained in monazite and allanite (possibly also in thorite). Therefore, at least to some extent, the lighter REE concentrate into the same minerals as the Th. Probably the behaviour of the lighter REE during metamorphism is also closely analogous to that of the Th. It was pointed out earlier that under the conditions of intermediate- to high-pressure granulite facies of metamorphism, the rocks become depleted of Th. Possibly the REE, the lighter REE especially, follow the Th and become concentrated in the rapakivi melt. During this stage, the Eu in part follows the Ca and becomes either enriched in the refractory residue or in anorthositic rocks by early accumulation of plagioclase from the melt, the rapakivitic melt itself becoming depleted of Eu.

Accordingly, the distribution and amounts of REE in rapakivi do not conflict with the hypotheses adopted in the present paper concerning the origin of rapakivi magma. Rather they do favour it.

At this point, an interesting analogy in trace element contents in rapakivi granites and in basic igneous rocks merits attention. Green and Ringwood (1967), in their monumental study on the genesis of basaltic magmas, pointed out that the minor elements K, Ti and P and the trace elements U, Th, Ba, Cs, Rb, Sr, Zr, Hf and REE (the lighter REE) are frequently found to be much more abundant in alkali olivine basalts and in some tholeiites of a continental environment than predicted by simple crustal fractionation from olivine-rich tholeiite or through differences in degree of partial melting of the same parental peridotite. The enrichment of these »incompatible elements» (inability to substitute to any appreciable extent in the major minerals of the upper mantle) in the magmas concerned was attributed by Green and Ringwood to the mechanism of »wall-rock reaction.» This takes place when there is a lack of a temperature contrast between the magma and the wall-rock. Cooling of the magma involves complementary processes of reaction with the wall-rock, including selective melting and extraction of the lowest melting fraction. The »incompatible elements» become highly concentrated in the lowest melting fraction. Green and Ringwood assume (op.cit., p. 177) that, under certain conditions, it is possible that an environment suitable for an extensive »wall-rock reaction» may occur under »low pressure» conditions, too, as, for instance, if magma segregation occurs at higher levels in the mantle or if continued magmatic activity causes wall-rock temperatures in the lower crust or top of the mantle to approach the magma temperature. The authors emphasized the differences between the nature of the highly enriched »incompatible elements» in a »wall-rock reaction» at low pressure and at high pressure. For example, at low pressure, plagioclase is a stable phase in the wall-rock mineralogy; and, as Sr substitutes for Ca in plagioclase, Sr will behave as a »compatible element.» Also Ti was regarded as exhibiting similar differences in behaviour at high and low pressures.

As examples of a low-pressure »wall-rock reaction» in a continental crustal environment, Green and Ringwood introduced the Ferrar dolerite in Antarctica and Tasmanian dolerites, which are highly enriched in K, Rb, U, Th but low in Sr and Ti in comparison with olivine and quartz tholeiites from oceanic islands and oceanic ridges.

The analogy in trace element composition in rapakivi and continental alkaline olivine basalt and some tholeiites is so remarkable that it cannot be due solely to pure coincidence. In the present author's mind, the existence of this analogy should be rather expected if the process considered responsible for the generation of the rapakivi melt really took place.

The basic difference between the model constructed by Bridgewater et al. (1974), discussed in the foregoing, and that outlined in the present paper is that the researches referred to consider the rise in temperature in the lower crust, which resulted in its partial melting, to have been due to the heat from the basaltic magma; the present author, for his part, takes the view that partial melting of the lower crust took place as early as the culmination stage of metamorphism associated with the orogeny when the isotherms rose upwards in the crust. The emplacement into the upper levels of the crust of the melt produced then took place during the postorogenic stage. Thus the rapakivi granites have a causal connection with the orogeny. Therefore the rapakivi granites should be called postorogenic, not anorogenic.

Sudovikov's model (1967), in turn, resembles the present author's model in that it is based on deep-seated regional metamorphism and partial fusion of the parent rock. In other details, the models are quite different. Sudovikov's model involves the rise of the rapakivi mass as a rheomorphic »migma,» while the present author's model involves the separation of the fluid phase from the refractory residue and the rise of the rapakivi mass as a magma. The emplacement process itself is postorogenic in both models.

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APPENDICES

Appendix 1

List of chemically analyzed rapakivi granite samples from the Laitila rapakivi massif

1. Tarkki granite. 85/IH/67, Lapijoki Eurajoki. (I. Haapala 1974, p. 164, anal. 1.).
2. » » . Tarkki, Eurajoki. (A. Laitakari 1928, p. 11).
3. Normal Laitila rapakivi. 30—2/AV/67—73, Hinnerjoki, Eura.
4. » » » ; small ovoidic. 27/AV/66—73, Lamssijärvi, Yläne.
5. » » » . 511/LC/68—73, Kylmäkorpi, Kalanti.
6. » » » . 327/LC/68—73, Untamala, Laitila.
7. » » » . 28/AV/66—73, Lemmi, Mynämäki.
8. » » » . Suontaka, Laitila. (A. Kahma 1951, p. 46, anal. 13).
9. » » » . Eurajoki Station, rail road cutting. (P. Eskola 1928. p. 22, anal. 6).
10. Normal Laitila rapakivi. Laitila (?). (Eskola 1930a, p. 101, anal. 1).
11. Kokemäki granite; approximately normal rapakivi. 29/AV/67—73, Peipohja, Kokemäki.
12. Coarse-grained rapakivi with a gradual change to normal rapakivi. 329/MT/67—73, Löyttilä, Eura.
13. Marginal even-grained modification of normal Laitila rapakivi. 32/KV/67—74, Elijärvi, Yläne.
14. Granite porphyry. 20/AV/66—73, Sydänmaa, Eurajoki.
15. » » . 242a/MT/67—73, Haukkavuori, Säkylä.
16. Marginal granite porphyry of normal rapakivi. 111/AV/74, Ihode, Pyhäranta.
17. Even-grained rapakivi granite (Lellainen granite). 205/MT/67—73, Lellainen, Eura.
18. Even-grained rapakivi. 17/AV/66—73, Lamminjärvi, Eura.
19. » » » . 30—1/AV/67—73, Hinnerjoki, Eura.
20. » » » . 30/KV/67—73, Elijärvi, Yläne.
21. » » » with scattered ovoids. 18/AV/66—73, Turajärvi, Eura.
22. » » » . 110/AV/74, Neittamo, Eura.
23. » » » ; topaz-bearing. 237/MT/67—74. Laajoki, Karjala.
24. » » » ; coarse-grained. 320/MT/67—74, Honkilahti, Eura.
25. » » » ; dark-coloured. 166/MVA/72—74, Malko, Laitila.
26. » » » . 169/MVA/72—74, Haaro, Laitila.
27. Porphyry aplite. 56/MT/67—73, Latvajärvi, Eura.
28. Aplite. Liesjärvi, Hinnerjoki. (P. Eskola 1928, p. 22, anal. 11).
29. Spotted granite. 21/AV/66—73, Kodisjoki.
30. » » . Kodisjoki. (P. Eskola 1928, p. 22, anal. 10).
31. » » . 164/MT/67—74, Lamssijärvi, Yläne.
32. » » . Suontaka, Laitila. (A. Kahma 1951, p. 32, anal. 9).
33. Ytö granite. 1—1/AV/66—73, Kusni, Laitila.
34. » » .102/AV/74, Kuloistensuo, Laitila.
35. Autolith in Ytö granite. 1—2/AV/66—73, Kusni, Laitila.
36. » » » » . 124/MVA/72—74, Ytö, Laitila.

37. Suutila granite. 23—1/AV/66—73, Suutila, Karjala.
38. » » . 100/AV/74, Karjalankylä, Karjala.
39. Autolith in Suutila granite. 23—2/AV/66—73, Suutila, Karjala.
40. » » » » . 101/AV/74, Karjalankylä, Karjala.
41. Katinhäntä aplite. 2/AV/66—73, Katinhäntä, Laitila.
42. Väkkärä granite. Väkkärä, Eurajoki. (A. Laitakari 1928, p. 10).
43. » » ; contact type. Luodonmaa, Linnamaa, Eurajoki. (I. Haapala 1974, p. 164, anal. 3).
44. Väkkärä granite; even-grained type. Linnamaa, Eurajoki. (I. Haapala 1974, p. 164, anal. 5).
45. Väkkärä granite; porphyritic type. Heikkilä, Eurajoki. (I. Haapala 1974, p. 165, anal. 6).
46. Väkkärä granite; slightly porphyritic. Koivuniemi, Eurajoki. (I. Haapala 1974, p. 165, anal. 7).
47. Väkkärä granite; coarse-grained type. Koivuniemi, Eurajoki. (I. Haapala 1974, p. 165, anal. 8).
48. Väkkärä granite; porphyritic type. 98/MK/67/ER/73, Eurajoki. (Personal communication by I. Haapala).
49. Even-grained rapakivi dike. 24/AV/66—74, Kohomussuo, Honkilahti, Eura.
50. » » » » . Suurikkala, Kalanti. (A. Hietanen 1943, p. 65).
51. Granite porphyry dike. 45/KV/67—74, Heinjoki, Yläne.
52. Quartz porphyry dike. 97B/IH/73, Tarkki, Eurajoki. (Personal communication by I. Haapala).

Appendix 2

Chemical analyses of different rapakivi varieties from the Laitila rapakivi massif.

Sample locaties and characterization of samples are given in Appendix 1.

Analysts:

1) Pentti Ojanperä (P.O.), A. E. O. Nordensvan (A.E.O.N.), Maria Hynönen (M.H.), Oleg von Knorring (O.v.K.), Naima Sahlbom (N.S.), Lauri Lokka (L.L.), Mervi Wiik (M.W.), and Elsa Ståhlberg (E.S.);

2) XRF-analyses of Rb, Sr, Ba, and Zr (if otherwise, stated in the Appendix) by Väinö Hoffrén (V.H.), and Maija-Leena Hagel (M-L.H.);

3) Emission spectrographic analyses of Sr and Zr by Ringa Danielson (R.D.), Arvo Löfgren (A.L.), and Ari Puisto (A.P.).

Appendix 2, contd

	Tarkki granite		Group of normal rapakivi granites					
	1	2	3	4	5	6	7	8
SiO_2	65.87	64.96	70.28	72.24	72.52	71.97	68.80	68.16
TiO_2	0.79	0.85	0.48	0.42	0.37	0.33	0.52	0.46
Al_2O_3 ...	13.61	14.26	14.04	13.37	13.87	13.70	16.24	14.37
Fe_2O_3 ...	1.68	1.25	0.58	0.68	0.80	0.64	0.72	1.95
FeO	5.49	6.02	3.47	2.91	2.01	2.21	2.08	2.07
MnO	0.08	0.10	0.05	0.06	0.05	0.05	0.07	0.04
MgO	0.75	0.54	0.39	0.11	0.17	0.04	0.29	0.50
CaO	1.98	2.45	1.85	1.64	0.78	1.60	2.25	1.45
Na_2O	2.43	2.80	2.73	2.49	2.49	2.62	2.81	1.83
K_2O	4.97	5.23	4.95	5.32	5.98	5.91	4.40	6.89
P_2O_5	0.30	0.05	0.11	0.07	0.07	0.04	0.12	0.11
CO_2	0.00	—	0.00	0.07	0.00	0.05	0.00	—
H_2O+ ..	1.26	1.20	0.50	0.66	0.97	0.48	0.76	1.20
H_2O- ..	0.10	0.13	0.06	0.08	0.07	0.04	0.07	0.32
F	0.25	—	0.23	0.24	0.24	0.25	0.16	0.23
Li_2O	0.0038*	—	0.008	0.009	0.008	0.007	0.005	—
Rb_2O	0.020	—	0.028	0.026	0.037	0.028	0.023	—
SrO	0.025	—	0.015	0.014	0.008	0.014	0.020	—
BaO	0.16	—	0.13	0.13	0.04	0.15	0.21	—
ZrO_2	0.082	—	0.042	0.047	0.037	0.038	0.051	—
	99.85	99.84	99.94	100.59	100.52	100.17	99.60	99.58
$-O=F_2$.	0.11	—	0.10	0.10	0.10	0.11	0.07	0.10
	99.74	99.84	99.84	100.49	100.42	100.06	99.53	99.48
Silicate analysis by [1])	P.O.	A.E.O.N.	M.H.					O.v.K.
with [2]) ...	V.H.		M-L.H.					
and [3]) ...	R.D.or A.L.(Zr)							

* Personal comm. by I. Haapala

Appendix 2, contd

	Group of normal rapakivi granites							
	9	10	11	12	13	14	15	16
SiO_2	68.79	70.42	72.01	71.48	69.35	68.99	70.77	71.71
TiO_2	0.38	0.52	0.26	0.47	0.53	0.58	0.44	0.37
Al_2O_3 ...	14.44	13.22	13.61	13.42	13.79	14.51	14.43	13.82
Fe_2O_3 ...	1.61	0.64	0.85	0.48	0.83	0.68	0.62	0.42
FeO	3.01	3.74	2.13	3.38	3.72	3.99	2.64	2.27
MnO	tr.	0.04	0.04	0.05	0.05	0.05	0.05	0.03
MgO	0.49	0.07	0.15	0.20	0.42	0.50	0.11	0.40
CaO	1.33	2.27	1.59	1.40	2.14	2.20	1.15	1.12
Na_2O	2.95	2.81	2.31	2.47	2.75	2.68	2.57	2.98
K_2O	6.85	5.21	6.38	5.62	5.12	5.24	5.05	6.02
P_2O_5	tr.	0.09	0.03	0.06	0.15	0.09	0.07	0.13
CO_2	—	—	0.00	0.18	0.12	0.09	0.05	0.00
H_2O+ ..	0.50	0.63	0.57	1.00	0.29	0.53	1.16	0.59
H_2O- ..		0.09	0.05	0.07	0.06	0.05	0.06	0.02
F	—	0.46	0.27	0.27	0.21	0.12	0.31	0.26
Li_2O	—	—	0.008	0.008	0.0065	0.006	0.009	0.0125
Rb_2O	—	—	0.025	0.026	0.025	0.021	0.034	0.034
SrO	—	—	0.013	0.013	0.014	0.018	0.009	0.003
BaO	—	0.13	0.20	0.11	0.16	0.18	0.11	0.09
ZrO_2	—	0.11	0.038	0.040	0.041	0.053	0.040	0.030
	100.35	100.45	100.53	100.75	99.78	100.58	99.68	100.31
$-O=F_2$.	—	0.19	0.11	0.11	0.09	0.05	0.13	0.11
	100.35	100.26	100.42	100.64	99.69	100.53	99.55	100.20
Silicate analysis by [1])	N.S.	L.L.	M.H.		P.O. & M.W.	M.H.		P.O. & M.W.
with [2]) ...			M-L.H.					
and [3]) ...								

	Various biotite rapakivis; mostly even-grained							
	17	18	19	20	21	22	23	24
SiO_2	77.01	76.74	76.42	74.98	73.52	76.22	74.94	73.82
TiO_2	0.20	0.24	0.27	0.28	0.35	0.26	0.22	0.33
Al_2O_3 ...	11.66	11.73	11.87	12.51	12.76	11.55	12.52	12.46
Fe_2O_3 ...	0.35	0.62	0.41	0.49	0.69	0.40	0.53	0.99
FeO	1.34	1.27	1.78	1.91	2.13	1.71	1.23	1.71
MnO	0.03	0.02	0.03	0.04	0.04	0.02	0.01	0.03
MgO	0.04	0.20	0.15	0.11	0.39	0.21	0.23	0.51
CaO	0.94	0.94	0.99	0.89	0.89	0.99	0.76	0.87
Na_2O	2.37	2.24	2.16	2.55	2.16	2.38	2.69	2.44
K_2O	5.08	5.17	4.48	5.38	6.28	5.10	5.96	5.20
P_2O_5	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.08
CO_2	0.09	0.08	0.00	0.00	0.00	0.00	0.00	0.09
H_2O+ ..	0.48	0.46	0.39	0.58	0.75	0.52	0.58	0.77
H_2O- ..	0.06	0.06	0.05	0.03	0.09	0.04	0.06	0.12
F	0.45	0.36	0.29	0.37	0.27	0.30	0.52	0.29
Li_2O	0.011	0.011	0.009	0.008	0.007	0.0083	0.0123	0.0085
Rb_2O	0.040	0.038	0.029	0.035	0.035	0.032	0.051	0.032
SrO	0.005	0.006	0.008	0.007	0.013	0.006	0.000	0.010
BaO	0.03	0.03	0.06	0.06	0.06	0.06	0.03	0.07
ZrO_2	0.026	0.028	0.027	0.032	0.050	0.026	0.024	0.033
	100.23	100.27	99.45	100.29	100.53	99.87	100.41	99.86
$-O=F_2$.	0.19	0.15	0.12	0.16	0.11	0.13	0.22	0.12
	100.04	100.12	99.33	100.13	100.42	99.74	100.19	99.74
Silicate analysis by [1])	M.H.					P.O. & M.W.		
with [2]) ...	M-L.H.							
and [3]) ...								

Appendix 2, contd

	Various biotite rapakivis; mostly even-grained							
	25	26	27	28	29	30	31	32
SiO_2	73.45	74.68	74.73	74.66	74.15	74.73	74.71	72.98
TiO_2	0.41	0.32	0.20	0.28	0.26	0.36	0.27	0.25
Al_2O_3 ...	12.34	12.26	13.01	12.40	12.79	12.10	12.03	12.28
Fe_2O_3 ...	0.65	0.62	0.98	0.65	0.60	0.19	0.72	1.64
FeO	2.39	1.88	1.02	1.63	1.78	2.19	1.65	1.67
MnO	0.03	0.02	0.03	0.02	0.05	0.01	0.02	0.03
MgO	0.21	0.60	0.04	0.07	0.04	0.09	0.16	0.21
CaO	1.20	1.04	0.81	0.96	0.74	0.96	0.81	1.02
Na_2O	2.27	2.27	2.58	2.71	2.39	2.01	2.35	2.04
K_2O	5.80	5.44	5.82	5.98	6.18	6.85	6.22	7.12
P_2O_5	0.06	0.04	0.01	0.02	0.01	0.06	0.03	—
CO_2	0.00	0.00	0.00	—	0.08	—	0.00	—
H_2O+ ..	0.59	0.66	0.78	0.26	0.61	0.50	0.64	0.80
H_2O- ..	0.10	0.06	0.05	0.04	0.05	0.03	0.04	0.16
F	0.16	0.18	0.40	0.32	0.32	0.22	0.48	0.33
Li_2O	0.0046	0.0078	0.007	—	0.007	—	0.0090	—
Rb_2O	0.025	0.027	0.047	—	0.036	—	0.037	—
SrO	0.009	0.007	0.005	—	0.008	—	0.004	—
BaO	0.09	0.09	0.01	—	0.03	—	0.03	—
ZrO_2	0.059	0.045	0.032	—	0.043	—	0.040	—
	99.85	100.25	100.56	100.00	100.17	100.30	100.25	100.53
$-O=F_2$.	0.07	0.08	0.17	0.13	0.13	0.09	0.20	0.14
	99.78	100.17	100.39	99.87	100.04	100.21	100.05	100.39
Silicate analysis by [1])	M.V.		M.H.	A.E.O.N.	M.H.	A.E.O.N.	P.O. & M.W.	E.S.
with [2]) ...	M-L.H.				M-L.H.		M-L.H.	
and [3]) ...								

	Ytö granite and related rocks								
	33	34	35	36	37	38	39	40	41
SiO_2	71.60	72.32	71.54	71.11	71.89	70.86	70.94	71.27	71.51
TiO_2	0.34	0.32	0.30	0.32	0.34	0.40	0.43	0.40	0.35
Al_2O_3 ...	14.42	13.63	14.14	14.11	12.18	13.95	14.28	13.80	14.24
Fe_2O_3 ...	0.87	0.70	0.61	0.63	1.30	0.63	0.81	0.68	0.75
FeO	1.94	1.92	2.06	2.30	3.15	2.57	2.48	2.46	2.29
MnO	0.04	0.03	0.04	0.03	0.04	0.04	0.05	0.03	0.05
MgO	0.43	0.38	0.08	0.37	0.37	0.50	0.53	0.46	0.31
CaO	1.18	1.00	0.88	1.04	1.17	1.22	0.97	1.07	1.20
Na_2O	2.85	2.85	2.54	2.80	2.77	2.90	2.64	2.80	2.82
K_2O	5.73	5.52	6.53	6.00	5.73	5.52	6.24	5.95	5.80
P_2O_5	0.09	0.10	0.09	0.12	0.10	0.12	0.11	0.11	0.04
CO_2	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00
H_2O+ ..	0.54	0.69	0.43	0.52	0.59	0.69	0.52	0.78	0.48
H_2O- ..	0.03	0.03	0.03	0.05	0.04	0.05	0.03	0.04	0.04
F	0.36	0.41	0.32	0.31	0.34	0.34	0.36	0.24	0.39
Li_2O	0.013	0.0138	0.014	0.0115	0.012	0.0133	0.02	0.0110	0.010
Rb_2O	0.044	0.041	0.046	0.049	0.040	0.037	0.047	0.044	0.038
SrO	0.009	0.006	0.008	0.008	0.009	0.010	0.008	0.010	0.009
BaO	0.05	0.04	0.07	0.07	0.07	0.06	0.02	0.05	0.04
ZrO_2	0.031	0.028	0.018	0.019	0.036	0.035	0.055	0.049	0.047
	100.57	100.03	99.75	99.87	100.26	99.95	100.54	100.25	100.41
$-O=F_2$.	0.15	0.17	0.13	0.13	0.14	0.14	0.15	0.10	0.16
	100.42	99.86	99.62	98.74	100.12	99.81	100.39	100.15	100.25
Silicate analysis by [1])	M.H.	P.O. & M.W.	M.H.	M.W.	M.H.	P.O. & M.W.	M.H.	P.O. & M.W.	M.H.
with [2]) ...	M-L.H.								
and [3]) ...									

Appendix 2, contd

	Väkkärä granite						
	42	43	44	45	46	47	48
SiO_2	74.20	73.02	75.32	74.40	74.57	74.60	74.63
TiO_2	0.36	0.31	0.17	0.07	0.03	0.07	0.06
Al_2O_3	12.48	12.95	12.27	13.25	14.26	13.08	13.82
Fe_2O_3	0.77	1.12	0.55	0.80	0.55	1.64	0.37
FeO	1.63	1.76	1.39	0.86	0.43	0.20	0.62
MnO	0.02	0.03	0.02	0.04	0.03	0.04	0.04
MgO	0.15	0.38	0.04	0.01	0.03	0.01	0.01
CaO	1.08	0.80	0.97	1.14	0.60	0.99	0.68
Na_2O	2.32	2.47	2.55	2.68	3.72	2.92	3.72
K_2O	6.01	5.55	5.22	5.01	4.48	5.02	4.90
P_2O_5	0.02	0.17	0.07	0.10	0.01	0.10	0.01
CO_2	—	0.00	0.00	0.00	0.00	0.00	0.00
H_2O+	0.65	1.00	0.63	0.64	0.51	0.47	0.38
H_2O-	0.22	0.14	0.07	0.08	0.07	0.03	0.06
F	—	0.39	0.67	1.33	0.90	0.88	1.06
Li_2O	—	0.01	0.01	0.04	0.10	0.05	0.05
Rb_2O	—	0.038	0.051	0.094	0.092	0.107	0.119
SrO	—	0.012	0.002	0.001	0.00	0.001	< 0.005
BaO	—	0.06	0.01	0.01	0.0	0.02	0.0
ZrO_2	—	0.027	0.030	0.011	0.00	0.008	< 0.0135
	99.91	100.24	100.04	100.57	100.38	100.24	100.55
$-O=F_2$	—	0.16	0.28	0.56	0.38	0.37	0.45
	99.91	100.08	99.76	100.01	100.00	99.87	100.10
Silicate analysis by ¹)	A.E.O.N.	P.O.					P.O. & M.W.
with ²)		V.H. (Rb and Ba)					M-L.H. (Rb, Ba)
and ³)		R.D. or A.L. (Sr and Zr)					A.P. (Sr, Zr)

	Dike rocks				Mean composition		
	49	50	51	52	53	Standard deviation	Number of determinations
SiO_2	75.29	74.00	71.47	73.59	72.58	2.60	52
TiO_2	0.30	tr.	0.42	0.02	0.34	0.16	51
Al_2O_3	11.90	14.65	13.41	15.04	13.32	1.02	52
Fe_2O_3	0.15	0.00	0.94	0.52	0.76	0.39	52
FeO	1.86	0.50	2.18	0.14	2.14	1.13	52
MnO	0.02	0.01	0.03	0.02	0.037	0.017	51
MgO	0.17	0.06	0.53	0.00	0.25	0.20	52
CaO	0.72	0.76	0.83	0.38	1.17	0.47	52
Na_2O	2.37	3.53	2.59	4.80	2.65	0.48	52
K_2O	6.05	6.53	5.82	4.13	5.63	0.67	52
P_2O_5	0.02	tr.	0.11	0.11	0.074	0.053	49
CO_2	0.00	—	0.00	0.00	0.023	0.043	43
H_2O+	0.59	0.36	0.92	0.57	0.65	0.23	52
H_2O-	0.03	0.04	0.12	0.09	0.071	0.052	51
F	0.33	—	0.25	0.30	0.38	0.23	48
Li_2O	0.0095	—	0.0100	0.01	0.014	0.017	43
Rb_2O	0.038	—	0.034	0.078	0.043	0.022	43
SrO	0.000	—	0.012	0.001	0.0084	0.0054	43
BaO	0.01	—	0.10	0.03	0.072	0.055	44
ZrO_2	0.028	—	0.046	0.0032	0.036	0.019	44
	99.89	100.44	99.82	99.83	100.25		
$-O=F_2$	0.14	—	0.11	0.13	0.16		
	99.75	100.44	99.71	99.70	100.09		
Silicate analysis by [1]	P.O. & M.W.	E.S.	M.W.	P.O. & M.W.			
with [2]	M-L.H.		M-L.H.	M-L.H. (Rb, Ba)			
and [3]				R.D. (Sr, Zr)			

Appendix 3

Niggli values and CIPW norms (weight norms) of the analyses in Appendix 2.

Sample localities and characterization of samples are given in Appendix 1.

The *a* columns have been calculated by excluding the F, CO_2, Li_2O, Rb_2O, SrO, BaO and ZrO from the Niggli values and the norms, the *b* columns by including them. In cases where the fluorine content is so high as to exhaust all the calcium for fluorite the *b* column in the norm is left blank. The equality sign (=) in the *b* column indicates the same figure as in the *a* column.

	Tarkki granite				Group of normal rapakivi granites			
	1		2		3		4	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*
Niggli values								
si	290.0	288.9	271.3	=	351.0	349.5	388.3	386.5
al	35.3	35.2	35.1	=	41.3	41.1	42.4	42.2
fm	31.0	30.9	28.7	=	19.8	19.7	17.0	16.9
c	9.3	9.6	11.0	=	9.9	10.2	9.5	9.7
alk	24.3	=	25.3	=	29.0	=	31.2	=
k	0.57	=	0.55	=	0.54	=	0.58	=
mg	0.159	=	0.117	=	0.147	=	0.052	=
qz	92.7	91.7	70.2	=	135.0	133.6	163.4	161.7
Weight norm								
ap	0.71	=	0.12	=	0.26	=	0.17	=
il	1.50	=	1.61	=	0.91	=	0.80	=
z		0.12				0.06		0.07
cc		0.00				0.00		0.16
fr		0.46				0.45		0.48
or	29.37	30.33	30.91	=	29.25	29.49	31.44	31.68
ab	20.56	=	23.69	=	23.10	=	21.07	=
an	7.86	6.58	10.90	=	8.46	7.13	7.68	5.81
C	1.35	1.65			1.09	1.54	0.70	1.34
wo			0.39	=				
mt	2.44	=	1.81	=	0.84	=	0.97	=
hm								
en	1.87	=	1.35	=	0.97	=	0.27	=
fs	7.54	=	8.80	=	5.19	=	4.20	=
Q	24.77	24.66	18.94	=	28.86	29.26	32.00	32.63
Qu	33.16	32.64	25.75	=	35.53	35.75	37.87	38.22
Or	39.32	40.14	42.03	=	36.02	36.03	37.20	37.11
Ab	27.53	27.22	32.22	=	28.45	28.22	24.93	24.68
100								
Qu	30.00	30.03	22.43	=	32.18	32.88	34.71	35.78
Or	35.57	36.93	36.60	=	32.62	33.14	34.10	34.74
Ab	24.90	25.04	28.06	=	25.76	25.96	22.86	23.11
An	9.52	8.01	12.90	=	9.43	8.01	8.33	6.37
100								

Group of normal rapakivi granites

	5		6		7		8	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*
Niggli values								
si	407.0	405.9	388.4	386.5	339.2	337.3	337.9	=
al	45.9	45.8	43.6	43.4	47.2	46.9	42.0	=
fm	14.4	=	13.1	=	13.7	13.6	19.7	=
c	4.7	4.8	9.3	9.6	11.9	12.3	7.7	=
alk	35.0	=	34.1	34.0	27.3	27.2	30.6	=
k	0.61	=	0.60	=	0.51	=	0.71	=
mg	0.098	=	0.025	=	0.156	=	0.187	=
qz	167.2	165.8	152.2	150.5	130.1	128.5	115.6	=
Weight norm								
ap	0.17	=	0.10	=	0.28	=	0.26	=
il	0.70	=	0.63	=	0.99	=	0.87	=
z		0.05		0.06		0.08		
cc		0.00		0.11		0.00		
fr		0.48		0.51		0.31		0.45
or	35.34	35.60	34.93	35.14	26.00	26.16	40.72	=
ab	21.07	=	22.17	=	23.78	=	15.49	=
an	3.41	1.80	7.68	5.86	10.38	9.72	6.48	4.86
C	2.05	2.59	0.18	0.81	3.05	3.26	1.53	2.12
wo								
mt	1.16	=	0.93	=	1.04	=	2.83	=
hm								
en	0.42	=	0.10	=	0.72	=	1.25	=
fs	2.51	=	3.08	=	2.50	=	1.51	=
Q	32.28	32.79	29.33	29.96	29.57	29.72	26.92	27.62
Qu	36.40	36.65	33.94	34.33	37.26	37.31	32.39	32.95
Or	39.85	39.79	40.41	40.26	32.77	32.84	48.98	48.58
Ab	23.76	23.55	25.65	25.40	29.97	29.85	18.63	18.47
100								
Qu	35.05	35.93	31.17	32.17	32.95	33.25	30.05	31.14
Or	38.37	39.01	37.11	37.73	28.98	29.27	45.44	45.91
Ab	22.88	23.09	23.56	23.81	26.50	26.60	17.28	17.46
An	3.70	1.98	8.16	6.29	11.57	10.88	7.23	5.48
100								

Group of normal rapakivi granites

Niggli values

	9		10		11		12	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*
si	318.1	=	351.8	350.9	384.8	382.6	377.9	376.4
al	39.4	=	38.9	38.8	42.9	42.6	41.8	41.6
fm	20.6	=	18.7	=	14.3	14.2	18.7	18.6
c	6.6	=	12.2	12.4	9.1	9.5	7.9	8.2
alk	33.4	=	30.2	30.1	33.7	33.6	31.6	=
k	0.60	=	0.55	=	0.65	0.64	0.60	=
mg	0.164	=	0.028	=	0.083	=	0.084	=
qz	84.4	=	130.9	130.3	150.0	148.0	151.4	149.9

Weight norm

	9 *a*	9 *b*	10 *a*	10 *b*	11 *a*	11 *b*	12 *a*	12 *b*
ap			0.21	=	0.07	=	0.14	=
il	0.72	=	0.99	=	0.49	=	0.89	=
z				0.16		0.06		0.06
cc						0.00		0.41
fr				0.93		0.55		0.54
or	40.48	=	30.79	=	37.70	37.93	33.21	33.44
ab	24.96	=	23.78	=	19.55	=	20.90	=
an	5.93	=	8.07	7.59	7.69	6.13	6.55	3.72
C				0.18	0.09	0.62	0.87	1.87
wo	0.28	=	1.09					
mt	2.33	=	0.93	=	1.23	=	0.70	=
hm								
en	1.22	=	0.17	=	0.37	=	0.50	=
fs	3.57	=	5.56	=	2.85	=	5.13	=
Q	20.36	=	27.45	28.17	29.31	29.82	30.14	31.20

	9 *a*	9 *b*	10 *a*	10 *b*	11 *a*	11 *b*	12 *a*	12 *b*
Qu	23.72	=	33.47	34.05	33.86	34.16	35.77	36.47
Or	47.18	=	37.54	37.21	43.56	43.45	39.42	39.09
Ab	29.10	=	28.99	28.74	22.58	22.39	24.81	24.43
100								

	9 *a*	9 *b*	10 *a*	10 *b*	11 *a*	11 *b*	12 *a*	12 *b*
Qu	22.19	=	30.47	31.19	31.10	31.92	33.19	34.95
Or	44.13	=	34.17	34.09	40.00	40.59	36.58	37.46
Ab	27.21	=	26.39	26.32	20.74	20.92	23.02	23.42
An	6.46	=	8.96	8.40	8.16	6.57	7.22	4.17
100								

	Group of normal rapakivi granites							
	13		14		15		16	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*
	Niggli values							
si	334.1	332.7	321.1	319.6	385.9	384.5	379.2	377.8
al	39.2	39.0	39.8	39.6	46.4	46.2	43.1	42.9
fm	21.2	21.1	21.6	21.5	15.8	15.7	15.0	14.9
c	11.0	11.3	11.0	11.3	6.7	7.0	6.4	6.5
alk	28.6	=	27.6	=	31.2	=	35.6	=
k	0.55	=	0.56	=	0.56	=	0.57	=
mg	0.142	=	0.161	=	0.057	=	0.210	=
qz	119.8	118.4	110.5	109.2	161.3	159.7	136.9	135.2
	Weight norm							
ap	0.36	=	0.21	=	0.17	=	0.31	=
il	1.01	=	1.10	=	0.84	=	0.70	=
z		0.06		0.08		0.06		0.05
cc		0.27		0.21		0.11		0.00
fr		0.40		0.23		0.62		0.51
or	30.26	30.45	30.97	31.14	29.84	30.11	35.57	35.91
ab	23.27	=	22.68	=	21.75	=	25.22	=
an	9.64	7.77	10.33	9.31	5.25	2.94	4.71	3.06
C	0.19	0.84	0.65	0.99	2.81	3.61	0.68	1.22
wo								
mt	1.20	=	0.99	=	0.90	=	0.61	=
hm								
en	1.05	=	1.25	=	0.27	=	1.00	=
fs	5.36	=	5.90	=	3.70	=	3.27	=
Q	26.53	27.19	25.45	25.76	32.38	33.18	27.22	27.70
Qu	33.14	33.61	32.18	32.37	38.56	39.02	30.93	31.19
Or	37.80	37.64	39.15	39.13	35.54	35.41	40.42	40.43
Ab	29.07	28.76	28.67	28.50	25.90	25.57	28.65	28.39
100								
Qu	29.58	30.66	28.46	28.98	36.29	37.72	29.36	30.15
Or	33.73	34.34	34.63	35.03	33.45	34.23	38.37	39.08
Ab	25.94	26.24	25.36	25.51	24.38	24.72	27.20	27.44
An	10.75	8.76	11.55	10.47	5.88	3.34	5.08	3.33
100								

	Various biotite rapakivis							
	17		18		19		20	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*
	Niggli values							
si	517.0	515.6	502.8	502.1	507.6	505.8	457.4	455.8
al	46.1	46.0	45.3	45.2	46.5	46.3	45.0	44.8
fm	9.9	9.8	12.1	=	13.6	13.5	13.2	=
c	6.8	=	6.6	6.7	7.1	7.2	5.8	6.0
alk	37.2	37.3	36.0	=	32.9	33.0	36.0	36.1
k	0.59	0.58	0.60	=	0.58	0.57	0.58	=
mg	0.040	=	0.162	=	0.109	=	0.076	=
qz	268.3	266.3	258.7	258.1	276.1	273.9	213.3	211.6
	Weight norm							
ap	0.05	=	0.07	=	0.07	=	0.07	=
il	0.38	=	0.46	=	0.51	=	0.53	=
z		0.04		0.04		0.04		0.05
cc		0.21		0.18		0.00		0.00
fr		0.92		0.73		0.59		0.76
or	30.02	30.34	30.55	30.87	26.47	26.73	31.79	32.05
ab	20.05	=	18.95	=	18.28	=	21.58	=
an	4.53	0.76	4.47	1.42	4.72	2.74	4.22	1.65
C	0.60	1.93	0.81	1.87	1.74	2.42	0.95	1.84
wo								
mt	0.51	=	0.90	=	0.59	=	0.71	=
hm								
en	0.10	=	0.50	=	0.37	=	0.27	=
fs	1.90	=	1.46	=	2.54	=	2.72	=
Q	40.90	42.31	41.03	42.13	43.29	43.97	36.34	37.27
Qu	44.96	45.64	45.32	45.82	49.17	49.42	40.51	41.00
Or	33.00	32.73	33.75	33.57	30.07	30.04	35.44	35.26
Ab	22.04	21.63	20.94	20.61	20.76	20.54	24.05	23.74
100								
Qu	42.82	45.27	43.19	45.12	46.67	47.94	38.69	40.27
Or	31.43	32.47	32.16	33.06	28.54	29.14	33.84	34.63
Ab	21.00	21.46	19.95	20.30	19.70	19.93	22.97	23.32
An	4.75	0.81	4.70	1.52	5.08	2.98	4.49	1.78
100								

Various biotite rapakivis

Niggli values

	21		22		23		24	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*
si	420.4	419.0	492.1	490.4	457.5	456.0	436.3	434.8
al	43.0	42.9	44.0	43.8	45.0	44.9	43.4	43.2
fm	16.7	16.6	13.3	=	10.9	10.8	17.5	17.4
c	5.5	5.6	6.8	7.0	5.0	=	5.5	5.7
alk	34.9	=	35.9	=	39.1	39.3	33.6	=
k	0.66	0.65	0.59	0.58	0.59	=	0.58	=
mg	0.199	=	0.152	=	0.193	=	0.257	=
qz	180.9	179.4	248.5	246.6	201.0	199.0	202.0	200.3

Weight norm

	21 *a*	21 *b*	22 *a*	22 *b*	23 *a*	23 *b*	24 *a*	24 *b*
ap	0.10	=	0.10	=	0.10		0.19	=
il	0.67	=	0.49	=	0.42		0.63	=
z		0.07		0.04				0.05
cc		0.00		0.00				0.21
fr		0.55		0.61				0.58
or	37.11	37.35	30.14	30.39	35.22		30.73	30.98
ab	18.28	=	20.14	=	22.76		20.65	20.65
an	4.15	2.34	4.65	2.60	3.51		3.79	1.31
C	0.89	1.51	0.41	1.11	0.36		1.43	2.29
wo								
mt	1.00	=	0.58	=	0.77		1.44	=
hm								
en	0.97	=	0.52	=	0.57		1.27	=
fs	2.84	=	2.42	=	1.48		1.83	=
Q	33.26	33.86	39.44	40.15	33.95		36.49	37.39

	21 *a*	21 *b*	22 *a*	22 *b*	23 *a*	23 *b*	24 *a*	24 *b*
Qu	37.52	37.84	43.96	44.28	36.93		41.53	42.00
Or	41.87	41.73	33.59	33.51	38.31		34.97	34.80
Ab	20.62	20.43	22.45	22.21	24.76		23.50	23.19
100								

	21 *a*	21 *b*	22 *a*	22 *b*	23 *a*	23 *b*	24 *a*	24 *b*
Qu	35.84	36.88	41.79	43.04	35.57		39.81	41.39
Or	39.99	40.67	31.94	32.58	36.90		33.52	34.30
Ab	19.70	19.90	21.34	21.59	23.85		22.52	22.86
An	4.48	2.55	4.93	2.79	3.68		4.14	1.45
100								

Various biotite rapakivis

	25		26		27		28	
	a	b	a	b	a	b	a	b
Niggli values								
si	424.9	423.6	440.3	438.7	455.0	454.0	445.7	=
al	42.1	41.9	42.6	42.4	46.7	46.6	43.6	=
fm	16.4	16.3	17.4	17.3	10.2	=	11.8	=
c	7.4	7.6	6.6	6.8	5.3	=	6.1	=
alk	34.1	=	33.4	33.5	37.8	37.9	38.5	=
k	0.63	=	0.61	=	0.59	=	0.59	=
mg	0.111	=	0.303	=	0.036	=	0.053	=
qz	188.4	187.1	206.6	204.9	203.6	202.3	191.9	=
Weight norm								
ap	0.14	=	0.10	=	0.02	=	0.05	=
il	0.78	=	0.61	=	0.38	=	0.53	=
z		0.09		0.07		0.05		
cc		0.00		0.00		0.00		
fr		0.32		0.36		0.82		0.65
or	34.27	34.43	32.15	32.37	34.39	34.66	35.34	=
ab	19.21	=	19.21	=	21.83	=	22.93	=
an	5.56	4.62	4.90	3.79	3.95	1.06	4.01	2.30
C	0.29	0.61	0.84	1.21	1.02	2.03		0.63
wo							0.26	
mt	0.94	=	0.90	=	1.42	=	0.94	=
hm								
en	0.52	=	1.49	=	0.10	=	0.17	=
fs	3.23	=	2.45	=	0.79	=	2.03	=
Q	33.86	34.14	36.53	36.84	35.32	36.38	33.12	33.99
Qu	38.77	38.39	41.57	41.67	38.59	39.17	36.24	36.84
Or	39.24	39.23	36.58	36.61	37.57	37.32	38.67	38.30
Ab	21.99	21.88	21.86	21.72	23.85	23.51	25.09	24.86
100								
Qu	36.45	36.95	39.37	39.96	36.99	38.73	34.72	35.94
Or	36.89	37.27	34.65	35.11	36.01	36.90	37.04	37.37
Ab	20.67	20.79	20.70	20.83	22.86	23.24	24.04	24.25
An	5.99	5.00	5.28	4.11	4.14	1.13	4.20	2.43
100								

Appendix 3, contd

	Various biotite rapakivis							
	29		30		31		32	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*

Niggli values

	29 *a*	29 *b*	30 *a*	30 *b*	31 *a*	31 *b*	32 *a*	32 *b*
si	445.8	444.7	450.3	=	456.1	454.9	409.9	=
al	45.3	45.2	43.0	=	43.3	43.2	40.7	=
fm	12.3	12.2	12.8	=	13.3	=	16.6	=
c	4.8	4.9	6.2	=	5.3	5.4	6.1	=
alk	37.6	37.7	38.1	=	38.1	38.2	36.6	=
k	0.63	=	0.69	=	0.63	=	0.70	=
mg	0.029	=	0.063	=	0.110	=	0.106	=
qz	195.3	193.9	198.0	=	203.6	202.1	63.4	=

Weight norm

	29 *a*	29 *b*	30 *a*	30 *b*	31 *a*	31 *b*	32 *a*	32 *b*
ap	0.02	=	0.14	=	0.07	=		
il	0.49	=	0.68	=	0.51	=	0.48	=
z		0.06				0.06		
cc		0.18				0.00		
fr		0.66		0.44		0.98		0.68
or	36.52	36.76	40.48	=	36.76	37.03	42.07	=
ab	20.22	=	17.01	=	19.89	=	17.26	=
an	3.61	0.85	3.76	2.80	3.82	0.39	3.32	2.64
C	0.85	1.82		0.35	0.03	1.24		0.25
wo			0.25				0.73	
mt	0.87	=	0.28	=	1.04	=	2.38	=
hm								
en	0.10	=	0.22	=	0.40	=	0.52	=
fs	2.44	=	3.29	=	2.03	=	1.36	=
Q	33.87	34.89	33.44	33.98	34.43	35.71	31.13	31.79

	29 *a*	29 *b*	30 *a*	30 *b*	31 *a*	31 *b*	32 *a*	32 *b*
Qu	37.38	37.98	36.77	37.15	37.80	38.55	34.41	34.89
Or	40.30	40.01	44.52	44.25	40.36	39.98	46.51	46.17
Ab	22.32	22.01	18.71	18.59	21.84	21.47	19.08	18.94
100								

	29 *a*	29 *b*	30 *a*	30 *b*	31 *a*	31 *b*	32 *a*	32 *b*
Qu	35.95	37.63	35.31	36.05	36.28	38.39	33.19	33.91
Or	38.76	39.65	42.75	42.94	38.74	39.81	44.86	44.87
Ab	21.46	21.81	17.96	18.04	20.96	21.38	18.41	18.41
An	3.83	0.91	3.97	2.97	4.03	0.42	3.54	2.82
100								

	Ytö granite and related rocks							
	33		34		35		36	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*
Niggli values								
si	374.2	373.0	399.3	398.0	392.2	390.6	375.3	373.9
al	44.4	44.3	44.4	44.2	45.7	45.5	43.9	43.7
fm	15.4	=	15.0	=	12.8	12.7	15.7	15.6
c	6.6	6.7	5.9	6.0	5.2	5.3	5.9	6.0
alk	33.6	=	34.7	34.8	36.3	36.4	34.5	34.6
k	0.57	=	0.56	=	0.63	0.62	0.59	0.58
mg	0.217	=	0.208	=	0.051	=	0.185	=
qz	140.0	138.4	160.5	158.8	146.9	144.9	137.2	135.5
Weight norm								
ap	0.21	=	0.34	=	0.21	=	0.28	=
il	0.65	=	0.61	=	0.57	=	0.61	=
z		0.05		0.04		0.03		0.03
cc		0.00		0.00		0.00		0.00
fr		0.72		0.82		0.64		0.62
or	33.86	34.23	32.62	33.00	38.59	38.99	35.46	35.82
ab	24.12	=	24.12	=	21.49	=	23.69	=
an	5.27	2.82	4.31	1.46	3.78	1.64	4.38	2.33
C	1.60	2.43	1.39	2.36	1.51	2.22	1.41	2.09
wo								
mt	1.26	=	1.02	=	0.88	=	0.91	=
hm								
en	1.07	=	0.95	=	0.20	=	0.92	=
fs	2.36	=	2.48	=	2.86	=	3.23	=
Q	29.11	29.91	31.06	32.04	28.72	29.38	27.95	28.59
Qu	33.42	33.89	35.38	35.93	32.34	32.70	32.09	32.45
Or	38.88	38.79	37.15	37.01	43.45	43.38	40.71	40.65
Ab	27.69	27.33	27.47	27.05	24.20	23.92	27.20	26.89
100								
Qu	31.52	32.84	33.73	35.36	31.02	32.11	30.55	31.61
Or	36.67	37.59	35.41	36.42	41.68	42.61	38.76	39.61
Ab	26.11	26.48	26.18	26.62	23.22	23.49	25.90	26.20
An	5.70	3.09	4.68	1.61	4.08	1.79	4.78	2.58
100								

Ytö granite and related rocks

	37		38		39		40	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*
Niggli values								
si	379.0	377.6	367.8	366.6	363.6	362.3	373.7	372.6
al	37.8	37.7	42.7	42.5	43.1	43.0	42.6	42.5
fm	22.1	22.0	17.7	17.6	18.0	=	17.2	17.1
c	6.6	6.8	6.8	6.9	5.3	5.4	6.0	6.1
alk	33.4	33.5	32.9	33.0	33.5	33.7	34.1	34.2
k	0.58	0.57	0.56	0.55	0.61	0.60	0.58	=
mg	0.131	=	0.219	=	0.225	=	0.209	=
qz	145.3	143.6	136.3	134.7	129.5	127.6	137.2	135.7
Weight norm								
ap	0.24	=	0.28	=	0.26	=	0.26	=
il	0.65	=	0.76	=	0.82	=	0.76	=
z		0.05		0.05		0.08		0.07
cc		0.18		0.00		0.00		0.00
fr		0.68		0.68		0.72		0.47
or	33.86	34.20	32.62	32.98	36.87	37.39	35.16	35.50
ab	23.44	=	24.54	=	22.34	=	23.69	=
an	3.88	2.37	5.27	2.99	4.09	1.59	4.59	3.02
C		0.49	1.27	2.04	1.68	2.51	1.07	1.59
wo	0.53							
mt	1.89	=	0.91	=	1.17	=	0.99	=
hm								
en	0.92	=	1.25	=	1.32	=	1.15	=
fs	4.22	=	3.61	=	3.27	=	3.35	=
Q	29.42	30.11	28.20	28.94	27.66	28.38	28.02	28.46

Qu	33.93	34.31	33.04	33.47	31.84	32.21	32.25	32.47
Or	39.05	38.98	38.21	38.15	42.45	42.43	40.47	40.50
Ab	27.03	26.71	28.75	28.39	25.72	25.36	27.27	27.03
100								

Qu	32.47	33.41	31.12	32.35	30.41	31.64	30.63	31.38
Or	37.37	37.95	35.99	36.87	40.54	41.68	38.44	39.15
Ab	25.87	26.01	27.08	27.44	24.56	24.91	25.90	26.13
An	4.28	2.63	5.81	3.35	4.50	1.78	5.02	3.33
100								

	Katinhäntä aplite		Väkkärä granite					
	41		42		43		44	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*
Niggli values								
si	374.5	373.4	442.2	=	421.3	419.8	479.0	477.7
al	44.0	43.8	43.8	=	44.0	43.9	46.0	45.9
fm	15.6	=	13.0	=	16.8	16.7	10.5	=
c	6.7	6.8	6.9	=	5.0	5.1	6.6	=
alk	33.7	33.8	36.3	=	34.3	=	36.9	37.0
k	0.58	0.57	0.63	=	0.60	0.59	0.57	=
mg	0.155	=	0.102	=	0.195	=	0.036	=
qz	139.7	138.4	197.2	=	184.4	182.6	231.4	229.6
Weight norm								
ap	0.10	=	0.05	=	0.40	=	0.17	
il	0.67	=	0.68	=	0.59	=	0.32	
z		0.07				0.05		
cc		0.00				0.00		
fr		0.79				0.77		
or	34.27	34.57	35.52	=	32.80	33.11	30.85	
ab	23.86	=	19.63	=	20.90	=	21.58	
an	5.69	2.97	5.23	=	2.86	0.26	4.36	
C	1.24	2.18	0.24	=	1.83	2.73	0.83	
wo								
mt	1.09	=	1.12	=	1.62	=	0.80	
hm								
en	0.77	=	0.37	=	0.95	=	0.10	
fs	3.10	=	1.80	=	1.85	=	1.86	
Q	28.58	29.54	34.40	=	34.77	35.67	37.73	
Qu	32.96	33.57	38.42	=	39.30	39.78	41.85	
Or	39.53	39.30	39.66	=	37.07	36.92	34.22	
Ab	27.52	27.12	21.92	=	23.63	23.30	23.94	
100								
Qu	30.93	32.48	36.30	=	38.07	39.66	39.92	
Or	37.09	38.02	37.47	=	35.91	36.81	32.64	
Ab	25.82	26.24	20.71	=	22.89	23.24	22.83	
An	6.16	3.26	5.52	=	3.13	0.29	4.61	
100								

Appendix 3, contd

	Väkkärä granite							
	45		46		47		48	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*
	Niggli values							
si	459.4	456.2	456.0	449.6	459.0	455.0	453.6	449.9
al	48.2	47.9	51.4	50.7	47.4	47.0	49.5	49.1
fm	8.5	8.4	5.2	5.1	8.9	8.8	5.1	=
c	7.5	=	3.9	=	6.5	=	4.4	=
alk	35.8	36.2	39.5	40.4	37.1	37.6	40.9	41.4
k	0.55	0.54	0.44	0.43	0.53	0.52	0.46	0.45
mg	0.011	=	0.053	=	0.010	=	0.018	=
qz	216.3	211.4	197.8	188.2	210.5	204.5	190.0	184.2
	Weight norm							
ap	0.24		0.02		0.24		0.02	
il	0.13		0.06		0.13		0.11	
z								
cc								
fr								
or	29.61		26.47		29.66		28.96	
ab	22.68		31.48		24.71		31.48	
an	5.00		2.91		4.26		3.31	
C	1.59		2.22		1.28		1.18	
wo								
mt	1.16		0.80		0.57		0.54	
hm					1.25			
en	0.03		0.08		0.03		0.03	
fs	0.88		0.34				0.81	
Q	37.06		34.33		36.55		32.43	
Qu	41.48		37.20		40.20		34.92	
Or	33.14		28.69		32.63		31.18	
Ab	25.38		34.11		27.18		33.90	
100								
Qu	39.28		36.06		38.40		33.72	
Or	31.38		27.81		31.17		30.11	
Ab	24.04		33.07		25.96		32.73	
An	5.30		3.06		4.47		3.44	
100								

Appendix 3, contd

	Dike rocks								Mean	
	49		50		51		52		53	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
Niggli values										
si	474.1	473.1	421.6	=	389.2	387.6	430.7	429.3	402.6	400.9
al	44.2	44.1	49.2	=	43.0	42.9	51.9	51.7	43.5	43.4
fm	12.2	=	2.9	=	18.2	18.1	3.1	=	15.3	=
c	4.9	=	4.6	=	4.8	5.1	2.4	=	7.0	7.1
alk	38.8	38.9	43.2	=	33.9	=	42.7	42.8	34.2	34.3
k	0.63	0.62	0.55	=	0.60	0.59	0.36	=	0.58	=
mg	0.131	=	0.173	=	0.236	=	0.000	=	0.135	=
qz	219.0	217.6	148.7	=	153.7	151.9	160.1	158.2	165.9	163.9
Weight norm										
ap	0.05	=			0.26	=	0.26		0.18	=
il	0.57	=			0.80	=	0.04		0.65	=
z		0.04				0.07				0.05
cc		0.00				0.00				0.05
fr		0.67				0.49				0.77
or	35.75	36.04	38.59	=	34.39	34.68	24.41		33.27	33.66
ab	20.05	=	29.87	=	21.92	=	40.62		22.42	=
an	3.44	1.06	3.77	=	3.40	1.85	1.17		5.32	2.60
C	0.19	1.01	0.39	=	1.60	2.12	2.25		0.92	1.85
wo										
mt	0.22	=			1.36	=	0.46		1.10	=
hm							0.20			
en	0.42	=	0.15	=	1.32	=			0.62	=
fs	2.83	=	0.94	=	2.59	=			2.81	=
Q	35.32	36.15	26.33	=	30.70	31.15	29.36		31.67	32.58
Qu	38.76	39.19	27.78	=	35.28	35.50	31.11		36.25	36.75
Or	39.23	39.07	40.71	=	39.53	39.52	25.86		38.08	37.96
Ab	22.01	21.74	31.51	=	25.19	24.98	43.03		25.67	25.29
100										
Qu	37.35	38.75	26.72	=	33.95	34.77	30.73		34.17	35.70
Or	37.80	38.63	39.15	=	38.04	38.70	25.54		35.90	36.88
Ab	21.21	21.49	30.31	=	24.24	24.46	42.51		24.19	24.57
An	3.64	1.13	3.83	=	3.76	2.07	1.22		5.74	2.84
100										

Appendix 4

REE, Hf, Th and U contents (ppm) determined with the method of instrumental neutron activation analysis, and Hf/Zr and Th/U ratios in different rapakivi varities of the Laitila massif.

Sample localities and characterization of samples are given in Appendix 1. The analyses are made of the same rock powders of which also the chemical analyses in Appendix 2 are.

Analyst: Riitta Zilliacus, Reactor Laboratory, Technical Research Centre of Finland, Otaniemi.
Zr for Hf/Zr ratios is derived from Appendix 2.

Hf/Zr and Th/U ratios in column 53 (mean) calculated from the mean composition and not from the individual ratios under Nos. 1—52.

Appendix 4, contd

	Tarkki granite	Group of normal rapakivi granites										
	1	3	4	5	6	7	11	12	13	14	15	16
La	82	77	99	98	108	74	166	73	94	66	75	80
Ce	193	173	172	187	191	163	360	190	196	161	165	141
Nd	107	90	71	90	76	69	159	87	89	74	79	58
Sm	16.9	19.0	21.3	17.4	13	13.1	28.6	13.3	14.8	11.2	16.7	13.8
Eu	2.75	1.57	1.68	0.76	1.89	2.35	3.49	1.56	2.01	2.19	1.42	0.82
Gd	—	15.3	—	—	—	—	25.7	—	—	12.7	12.8	—
Tb	2.7	2.47	1.72	1.69	1.80	1.86	4.38	2.34	1.9	1.81	1.59	1.3
Dy	16.7	17.9	14.8	11.5	13.3	13.2	31.1	16.0	12.1	13.6	11.4	9.2
Tm	2.0	1.63	0.56	0.94	0.95	1.43	3.19	1.52	1.5	1.25	1.37	1.1
Yb	8.9	7.35	3.97	5.63	6.80	5.69	14.8	6.71	5.9	5.24	5.20	3.2
Lu	1.3	1.40	0.42	0.52	1 24	1.48	2.28	1.04	1.1	< 0.3	1.35	0.8
Hf	17.0	13.1	11.1	6.78	7.17	13.7	13.7	12.7	9.8	18.1	11.3	9.1
Th	17.2	15.5	19.9	5.80	31.0	15.0	23.4	18.8	23.0	12.8	44.5	45.3
U	2.5	4.45	4.19	6.71	6.10	2.26	5.03	4.26	3.2	2.92	6.77	3.4
Hf/Zr ...	0.028	0.042	0.032	0.025	0.026	0.036	0.049	0.042	0.033	0.046	0.038	0.041
Th/U	6.88	3.48	4.75	0.86	5.08	6.64	4.65	4.41	7.19	4.38	6.57	13.32

Appendix 4, contd

	Various biotite rapakivis												
	17	18	19	20	21	22	23	24	25	26	27	29	31
La	110	112	117	104	128	73	102	107	101	91	196	97	135
Ce	269	260	203	184	233	106	223	228	219	176	368	202	283
Nd	101	113	89	82	105	55	72	83	123	70	139	87	100
Sm	13.4	16.1	21.0	22.7	23.5	11.6	13.0	14.7	19.3	15.9	26.7	14.7	19.4
Eu	0.60	0.67	0.92	0.89	1.09	0.73	0.43	1.11	1.23	1.06	0.60	0.57	0.64
Gd	—	15.2	—	—	—	—	—	—	—	—	—	—	—
Tb	2.19	2.26	1.36	1.99	2.35	1.5	1.7	1.9	2.5	1.8	2.57	1.75	2.8
Dy	16.2	15.5	9.96	16.1	17.1	5.4	5.2	12.9	16.7	12.9	22.0	12.3	22.5
Tm	1.84	1.47	0.73	1.14	1.17	1.3	1.9	1.5	1.5	1.4	1.38	1.27	2.2
Yb	8.26	7.05	4.88	7.38	8.20	5.5	7.3	6.1	7.2	6.0	10.7	5.50	10.0
Lu	1.30	1.10	1.32	0.59	1.44	1.2	1.4	1.1	1.3	1.1	1.20	1.18	1.7
Hf	7.86	8.53	6.47	8.00	11.1	28.6	8.4	9.9	12.9	11.4	8.39	13.3	14.3
Th	44.8	44.2	49.6	27.4	40.7	8.3	70.7	39.4	25.5	30.4	69.2	39.2	77.8
U	9.34	11.3	11.1	6.79	9.06	5.4	7.0	4.5	5.4	3.3	12.3	6.99	5.9
Hf/Zr ...	0.041	0.041	0.032	0.033	0.030	0.151	0.047	0.041	0.029	0.035	0.035	0.042	0.048
Th/U	4.80	3.91	4.47	4.04	4.49	1.54	10.10	8.76	4.72	9.21	5.63	5.61	13.19

Generalized Geologic Map
of the
Laitila Rapakivi Massif

1. Orogenic rocks — SVECOFENNIAN
2. Normal Laitila rapakivi
3. Granite porphyry
4. Biotite rapakivi
5. Marginal Ytö granite and Suutila granite
6. Central Ytö granite and Katinhäntä aplite
7. Tarkki granite
8. Väkkärä granite
9. Anorthosite
10. Olivine diabase
11. Sandstone
12. Chemically analyzed sample; sampling site indicated
13. Chemically analyzed sample; probable sampling site indicated
14. Chemically analyzed sample; sampling site known only approximately

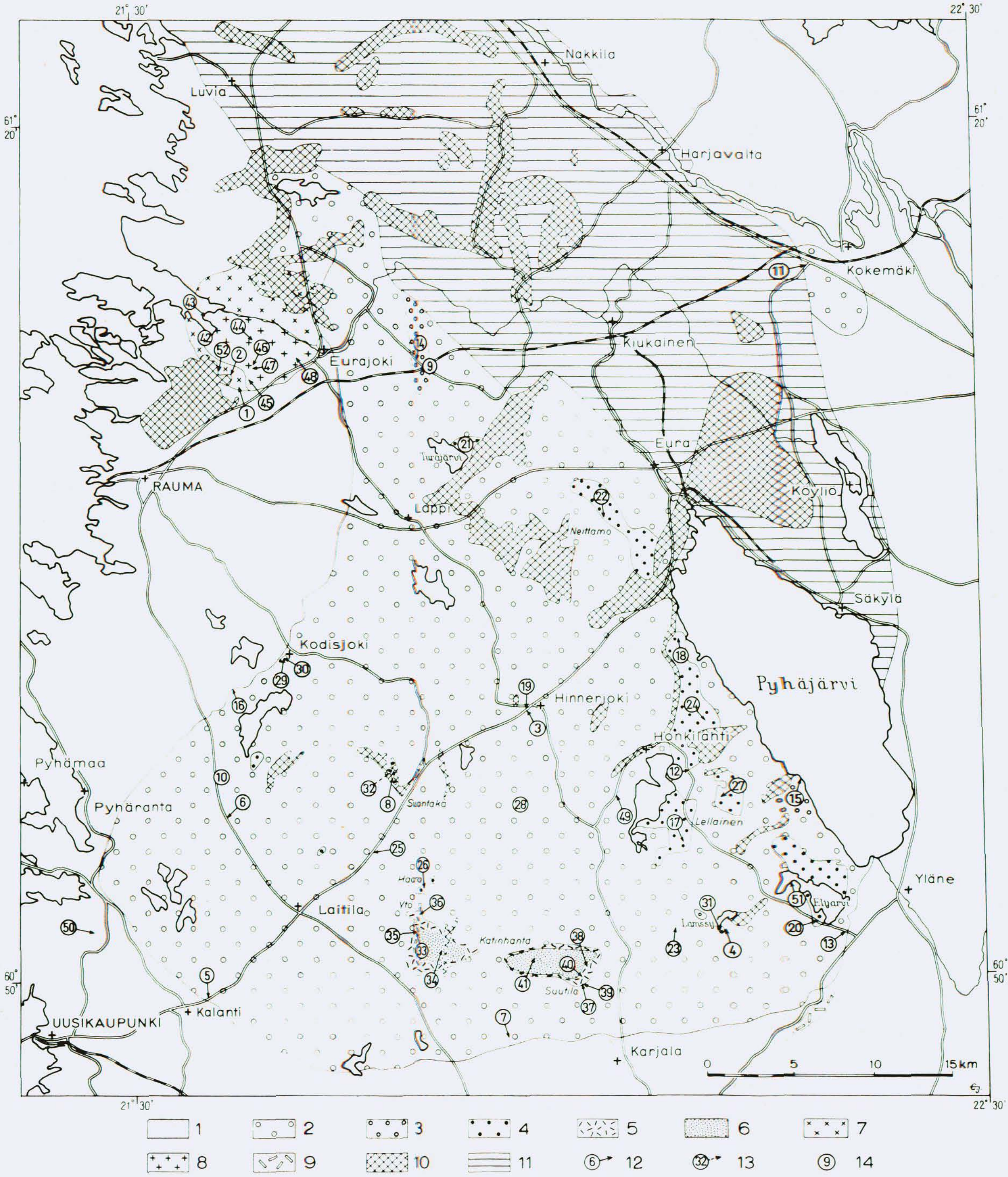
5–6: Ytö granite and related rocks

7–8: Eurajoki complex

2–9: SUBJOTNIAN

10–11: JOTNIAN

The map is based on the maps of Laitakari (1925), Kahma (1951), Haapala and Ojanperä (1972), and on new mapping in the southern part of the massif by the present author with his assistants.



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