Geological Survey of Finland

Bulletin 255

(formerly Bulletin de la Commission Géologique
de Finlande)

On the contact aureole of the Wiborg rapakivi granite massif in southeastern Finland

by Atso Vorma

Geologinen tutkimuslaitos · Otaniemi 1972

Geological Survey of Finland, Bulletin 255
(formerly Bulletin de la Commission Géologique de Finlande)

ON THE CONTACT AUREOLE OF THE WIBORG RAPAKIVI GRANITE MASSIF IN SOUTHEASTERN FINLAND

BY

ATSO VORMA

WITH ONE FIGURE AND THREE TABLES IN THE TEXT AND ONE APPENDIX

GEOLOGINEN TUTKIMUSLAITOS
OTANIEMI 1972

ISBN 951-690-000-3

Helsinki 1972. Valtion painatuskeskus

CONTENTS

Page
Introduction 5
Conditions prior to the emplacement of the rapakivi 6
  Grade of regional metamorphism 6
  Assumed history of the potash feldspar of plutonic rocks of the Svecofennidic belt 7
The contact aureole 8
  The contact aureole in the light of mineral parageneses 8
  Potash feldspar of plutonic rocks in the aureole 10
    Sampling 10
    X-ray investigation 10
    Width of the aureole 17
    Physical conditions in the aureole 17
    Relationship between the rapakivi variety and the nature of the potash feldspar in the aureole 18
    Observations of alkali feldspars in the aureole 18
  Notes on the behavior of other minerals of plutonic rocks in the aureole 20
    Cummingtonite 20
    Hornblende 21
    Biotite 21
Notes on the deformation of the country rock of the rapakivi 22
Discussion 22
References 26
Acknowledgments 28

18544—71

Vorma, Atso 1972: On the contact aureole of the Wiborg rapakivi granite massif in southeastern Finland. *Geological Survey of Finland, Bulletin 255.* 28 pages, 1 figure, 3 tables, 1 plate.

Potash feldspars from Svecofennidic plutonic rocks around the Wiborg rapakivi massif were studied to determine their thermal state. Around the Wiborg massif there is a thermometamorphic aureole about five kilometers broad, in which the initial microcline was transformed into orthoclase owing to the heat generated by the rapakivi. The orthoclase aureoles around the small satellite massifs of Suomenniemi, Mäntyharju and Onas are much narrower, and in places they seem to be lacking.

Some hornfelses are discussed. The emplacement temperature of the rapakivitic magma evidently exceeded 800°C.

The age relationship between the Suomenniemi massif and the main Wiborg massif is discussed. The Suomenniemi massif is evidently older than the Wiborg massif.

The general nature of the thermometamorphic aureoles around different granitic rocks is reviewed in the light of potash feldspar studies.

INTRODUCTION

This study deals with the contact aureole around the anorogenic Wiborg rapakivi granite pluton emplaced into the Svecofennidic belt about 1 700 million years ago (Kouvo 1958, Kouvo and Simonen 1967). The country rock of the rapakivi consists of metasediments penetrated by Svecofennidic plutonic rocks — gabbros, diorites, quartz diorites, granodiorites and granites — about 1 900 million years ago (Kouvo and Simonen 1967). Prior to the emplacement of the rapakivi, the postmetamorphic (metamorphism related to the Svecofennokarelidic orogeny) uplift and the erosion of the Svecofennidic belt were far advanced. Cratonization is revealed by, e.g., the Subjotnian diabase dike swarm which, slightly older than the rapakivi, cuts the Svecofennidic belt rectilinearly (Laitakari 1969, pp. 59—60). The rapakivigranite intrusion is shallow (Vorma 1971, pp. 60—61) or, in Buddington's (1959, p. 676) classification, epizonal.

The petrography and petrology of the Wiborg rapakivi granite has recently been described by Simonen and Vorma (1969) and by Vorma (1971). In the latter paper, emphasis is laid on the behavior of alkali feldspars during the consolidation of the composite pluton; the order-disorder phenomena in alkali feldspars in submagmatic temperatures are given particular attention.

The study at hand is mainly concentrated on establishing the thermometamorphic aureole in which, owing to the heat produced by rapakivi, the potash feldspar gained a higher thermal state than it had prior to the emplacement of the rapakivi. Potash feldspars present exclusively in the plutonic country rocks are studied. To obtain more information on the temperature of the emplacement, some previously published data on contact hornfelses are discussed.

Alkali feldspars from granodiorites occurring in the northeastern contact zone of the rapakivi granite, i.e., in the neighborhood of Lappeenranta, have earlier been studied by Vorma (in Marmo *et al.* 1963, pp. 66—70 and Vorma 1965, pp. 33—34). Even though the regional distribution of the monoclinic potash feldspar, as known in 1963, indicated that the orthoclase was mainly a product of thermometamorphism caused by the rapakivi granite, the then scanty data suggested that it was not necessary to take into account the influence of the rapakivi granite (Marmo *et al.* 1963, p. 68). The results reported by Kornfält (1969), especially with respect to the bahavior of the alkali feldspars in the country rocks of the Subjotnian Ragunda rapakivi massif in Sweden, persuaded the present author to re-evaluate his previous interpretation. Kornfält submits that the heat from the rapakivi intrusion converted, in a rather wide zone, the original triclinic potash feldspar of the surrounding rocks into a strictly monoclinic form. Also, the work of Eskola (1951, especially pp. 38—41) on the Pitkäranta area, northeast of Lake Ladoga, in which he established a pronounced »orthoclase province» near the border of the Salmi rapakivi massif, inspired the present author to do further work with the country rocks of the Finnish part of the Wiborg rapakivi massif and especially with their alkali feldspars.

CONDITIONS PRIOR TO THE EMPLACEMENT OF THE RAPAKIVI

Grade of regional metamorphism

At such distances from the contact of the Wiborg rapakivi massif that the thermometamorphism produced by it did not play any role, the country rocks are supracrustals, which are migmatized and granitized in many places, as follows:

Metapelites:	plagioclase-biotite gneisses
	garnet-biotite gneisses
	cordierite-biotite gneisses
	sillimanite-biotite gneisses
	(Note: potash feldspar only seldom coexists with sillimanite and/or cordierite; neither kyanite nor andalusite are met with)
Quartzites:	sillimanite quartzites
Calcareous rocks:	wollastonite limestones
	diopside limestones
Basic rocks:	amphibolites
	diopside amphibolites
	hornblende gneisses
	diopside gneisses

These assemblages reflect high-grade regional metamorphism under low-pressure conditions of the amphibolite facies. According to Winkler (1967), it corresponds to the sillimanite-cordierite-muscovite-almandine subfacies of the cordierite-amphibolite facies of the Abukuma-type metamorphism, and occasionally it reaches the sillimanite-cordierite-orthoclase-almandine subfacies of the same amphibolite facies.

Assumed history of the potash feldspar of plutonic rocks of the Svecofennidic belt

The present study deals mainly with granodiorites occurring as country rock of rapakivi. In addition, some data on quartz diorites and granites are presented.

The granodiorites and quartz diorites are generally regarded as synkinematic upper-catazonal rocks that were metamorphosed, more or less, during the Svecofennokarelidic orogeny. Their potash feldspar originally crystallized in monoclinic form. After the magmatic crystallization at submagmatic temperatures or during the regional metamorphism, the amount and pressure of pore fluid in a supercritical state — aqeous fluid — increased enough to cause the monoclinic orthoclase to become transformed into triclinic microcline. The majority of the granodiorites and quartz diorites in southern Finland are likely to be microcline-bearing even though orthoclase-bearing varieties may occur locally (see, Matisto 1962, Marmo *et al.* 1963).

Vorma suggested (1971) that, in all probability, the Si/Al ordering in rapakivi granite alkali feldspar mainly depends on the action of pore fluid at submagmatic temperatures. In rapakivi granite, the thermal state in alkali feldspar decreases gradually from olivine-bearing hornblende granite, over hornblende granite to biotite granite and dike rocks. To a certain degree, the chemical potential of H_2O also regulated the crystallization of anhydrous and hydrous Fe-Mg silicates. By analogy, it may be presumed, although no adequate data for testing the presumption are available as yet, that the Si/Al ordering in the potash feldspar of the Svecofennidic synkinematic plutonic rocks is farthest advanced in the biotite-rich varieties but less so in the hornblende-rich and, especially, the pyroxene-bearing varieties. Thus it is quite understandable that some granodiorites and quartz diorites contain potash feldspar in a high thermal state also outside the thermometamorphic aureole around the rapakivi massif.

To an overwhelming extent, the granites in the study area evidently are late-kinematic Svecofennidic plutonic rocks (see, Simonen 1960, p. 64) and belong to Sederholm's (1932) second group of granites. The granitization phenomena relate in one way or another to these granites (see, Sederholm 1926, Simonen 1960, pp. 64—72, Härme 1965, Marmo 1967a and 1967b). The characteristics indicate crystallization in places from hydrous silicate melt and in other places to an origin through granitization produced by the aqueous fluid expelled from the hydrous silicate melt (see, Jahns and Burnham 1969). In these granites, the cross hatching in the potash feldspar proves the potash feldspar to have crystallized originally in monoclinic form (see, Laves 1950). Owing to the high volatile pressure at temperatures between 400° and 500°C, the thermal state almost everywhere decreased to correspond to that of nearly maximum microcline. Only exceptionally has orthoclase been observed to be the main potash feldspar of the late-kinematic granites.

Summing it up: Prior to the intrusion of the rapakivi granite, the synkinematic and late-kinematic plutonic rocks contained potash feldspar mostly in a low thermal state. Only occasionally did the potash feldspar exhibit monoclinic symmetry indicating higher thermal states.

THE CONTACT AUREOLE

The contact aureole in the light of mineral parageneses

Because the supracrustal rocks of the country rock of the rapakivi were metamorphosed during the Svecofennokarelidic orogeny under the low-pressure conditions of amphibolite facies, they are characterized by mineral parageneses that do not deviate much from those belonging to the contact-metamorphic hornblende-hornfelds facies. Therefore, the contact aureole cannot be divided by conventional procedures into different hornfelds zones. Here and there, mineral assemblages of the pyroxene-hornfels facies representing an innermost contact zone have been observed. On the other hand, mineral assemblages characteristic of the albite-epidote-hornfels facies have also been discovered quite near the contact. These assemblages deviate so much from the usual ones in the surrounding Svecofennidic belt that it seems advisable to review the most important of them, especially since they render an estimation of the minimum temperature of the emplacement possible.

Pyroxene-hornfels facies (Numbers from one to six in Plate 1.)

1. Hackman (1933) described a contact in the northeastern contact zone between quartz diorite and rapakivi. The quartz diorite xenoliths in the rapakivi were altered into hypersthene-plagioclase-diopside-biotite (+ilmenite+quartz) hornfels.
2. Hackman (1934) also described hypersthene-bearing hornfelses occurring in basic rocks as large inclusions in rapakivi in different localities south of Lappeenranta.
3. Vorma (1965) mentioned a hypersthene gneiss occurring at an immediate contact with rapakivi north of Lappeenranta. In the author's present view, the rock is a hypersthene hornfels. Later studies of samples collected between sites 1 and 3 have revealed numerous instances of diopside-bearing hornfelses.
4. Simonen and Tyrväinen informed the author about the three pyroxene gneisses shown on the Savitaipale map quadrangle, scale 1 : 100 000 (Simonen and Tyrväinen 1965). All three pyroxene gneisses are rich in hypersthene, and the two eastern localities also bear diopside. According to the investigators cited, all three are products of thermometamorphism caused by the rapakivi. The hypersthene-bearing rocks cover quite extensive areas, measuring hundreds of meters across. Further away from the contact, the hypersthene-hornfels zone is succeeded by cordierite-biotite gneisses. Considering the high grade of the regional metamorphism, these rocks do not form an outer zone of contact aureole.

5. Savolahti (1956, 1962) described, from the western contact of the satellite rapakivi massif at Mäntyharju, a 5 cm broad pyroxene-hornfels zone against biotite rapakivi. According to Savolahti (1962, pp. 48—50 and 76), the hornfels contains abundant potash feldspar — which is almost entirely lacking in the rock with an identical bulk chemical composition situated farther than 5 cm from the contact — as well as plagioclase, hypersthene, hornblende, pigeonite and some biotite and chlorite. The pigeonite was identified by optical methods: $2V\gamma$ agrees with that of pigeonite but not with the indices of refraction given, which do apply to diopside-hedenbergite. Considering the environment of the mineral and the inconsistency in the optical data, it is evident that the mineral is diopside-hedenbergite and the assemblage belongs to the pyroxene-hornfels facies with minor retrograde reactions. Noteworthy is the fact that amphibole occurs as narrow rings around pyroxene. Presumably, the conditions of the pyroxene-hornfels facies lasted only for a short time.
6. Lehijärvi (1964) described a hypersthene-cordierite hornfels from the western contact of rapakivi. Basic schists (biotite-hornblende gneisses and amphibolites) intercalated with mica gneisses occur there in contact with rapakivi. According to Lehijärvi (personal communication), the hypersthene-cordierite hornfels is less than 100 meters broad measured perpendicular to the contact line. The dip of the contact is not known. Thus no estimate of the actual width of the pyroxene-hornfels zone can be given. Lehijärvi (*op.cit.*) regards this hornfels as analogous to the classical pyroxene hornfelses in the Oslo area.

Turner (1968, p. 258) accepts the lower limit of temperature at 1 kb pressure of H_2O to be about 650°C for the mineral assemblages characterizing the pyroxene-hornfels facies. Winkler (1967, p. 79) places the lower limit of the orthopyroxene subfacies of the K-feldspar—cordierite—hornfels facies at 1 kb pressure of H_2O at about 700°C. Because the temperature of the magma cannot be reached in the country rock — xenoliths are exceptions — and when also the local areal extent of the pyroxene hornfelses are taken into consideration, it may be concluded that the intrusion temperature of the rapakivi must have been considerably higher than the figures given, evidently somewhat higher than 800°C.

Simonen (1961) estimated that the feldspar equilibrium temperature of wiborgitic rapakivi is about 730°C. For the Salmi rapakivi massif northeast of Lake Ladoga, Sviridenko (1968) reports higher crystallization temperatures, based on the composition of titaniferous magnetite: wiborgite 880°C, even-grained granite 900°C, pyterlite 800°C and uneven-grained granite 940°C.

Albite-epidote-hornfels facies

According to Yletyinen (1952), the metamorphic basic volcanic rocks with a mineral assemblage of the amphibolite facies at Koskenkylä, close to the southwestern contact of the massif, change at a distance of about 100 m from the contact to an assemblage of the greenschist facies (locality 7 in Plate 1). Yletyinen attributed this change to the thermometamorphism produced by rapakivi. If this interpretation is correct, then the designation albite-epidote-hornfels facies should be used. In any case, at the locality in question, the thermal gradient caused by the rapakivi was either extremely steep, allowing the conditions of the albite-epidote-hornfels facies to be reached at a distance as short as 100 m from the contact, or then the water pressure was so high that retrograde reactions led to the formation of low-temperature mineral assemblages after the massif had cooled down and the gradient had become gentler, with a subsequent drop in the temperature.

The occurrence of contact hornfelses shows that the Wiborg rapakivi created a thermal dome, in which a steep gradient developed at the contacts. Owing to the large size of the massif, the gradient at first, over a period of hundreds of thousands — perhaps millions — of years, became gentler without any appreciable decrease in the contact temperature. During this stage, the country rock underwent progressive thermometamorphism. Owing to the former mineral assemblages of the amphibolite facies, the progressive stage left no clear marks. Pyroxene hornfelses are to be found only in the immediate vicinity of the contact and in the xenoliths.

Potash feldspar of plutonic rocks in the aureole

Sampling

The phenocryst and/or porphyroblastic potash feldspars were picked out by hand. Splinters of the even-grained specimens as well as of the matrix of the porphyritic and/or porphyroblastic varieties were crushed and the feldspars were separated by using heavy liquids. Table 1 lists the specimens from which potash feldspar concentrates were made. The characteristics of the feldspar and the specimen itself are included in the list.

X-ray investigation

Smear mounts were made of each of the potash feldspar concentrates and X-ray diffractometer patterns were run, using filtered copper radiation. The patterns were estimated in accordance with the method used by Vorma (1971, p. 42) on the rapakivi granite alkali feldspars. The following tentative structural types based on the 131 and $1\bar{3}1$ reflections were used:

I	Orthoclase only
I/II	Orthoclase with subordinate high microcline
II	Orthoclase with high microcline or high microcline only
II/III	Orthoclase with subordinate intermediate microcline
III	Orthoclase with intermediate microcline (single broad peak; unresolved)

IV Orthoclase with intermediate microcline (three peaks)

III/V Nearly maximum microcline or intermediate microcline with subordinate orthoclase or high microcline

V Intermediate microcline or maximum microcline only

For examples of the reflection types on which the tentative structural types I—V are based, see Fig. 1.

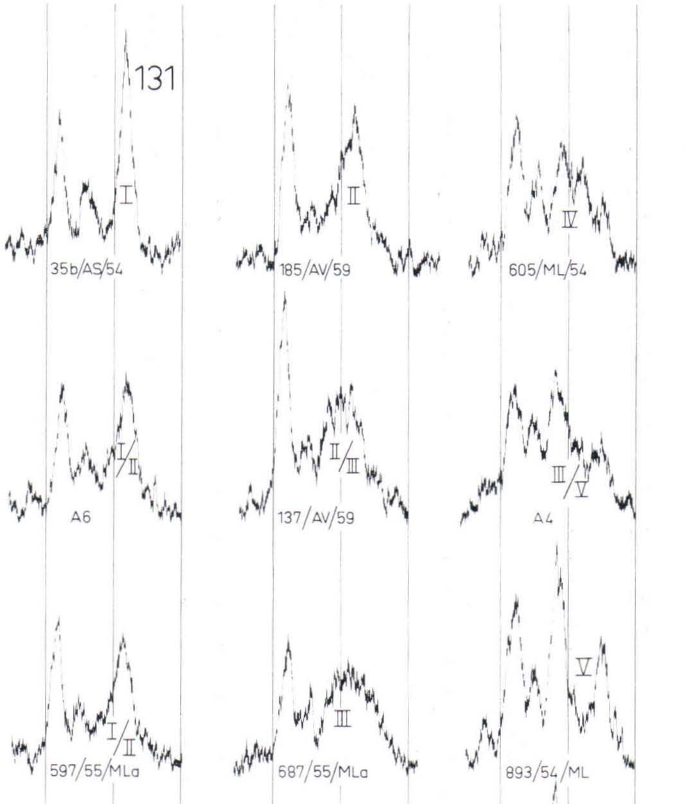


FIG. 1. Examples of the reflection types on which the tentative structural types I—V are based (from Vorma 1971, p. 43).

TABLE 1

Specimens of plutonic rocks around the Wiborg rapakivi massif investigated for their potash feldspar by X-rays.

Specimen number	Rock type [1]	Colour [2]	Grain size [3]	Foliation [4]	Reflection type		Fe-Mg silicate paragenesis (+muscovite) [6]							Remarks
					Matrix	Phenocrysts or porphyroblasts	Cummingtonite	Hornblende	Biotite	Chlorite	Muscovite [5]	Garnet	Epidote	
1	Gd	g	m	f	III				x	(x)		x		
2	Gd, Ph	rg	m	f	I/II	II/III			x		(x)			
3	Gd	lg	m	f	V				x			x		
4	Gd	rg	m	ff	IV				x			x		
5	Gd	g	mc	f	II				x	x		x		
6	G	lr	c	n	V				x		x	x		
7	G	r	c	n	V				x	x				
8	G	rg	s	f	V				x					
9	U	lg	mc	f	V					x			x	
10	Gd, Ph	rg	m	f	V				x		x			
11	Gd	rg	m	f	V				x		x			
12	G	g	mc	f	V				x					
13	Gd	g	c	ff	V	V			x	x	x			augen gneissose
14	Gd	rg	m	f	V				x	x				
15	G	r	m	f	V				x	x				
16	Qd	rg	m	f	V			x	x				x	
17	Qd	dr	s	ff	I			x	x	x				
18	Gd	lg	m	ff	V					x	x			
19	G	rg	s	f	V				(x)	x	x			
20	G, Ph	rg	m	f	V	V				x	x			
21	Gd	g	m	f	III				x	x				
22	Gd	rg	m	f	III				x	x				
23	Gd	g	s	f	V				x					
24	G	g	mc	f	V				x					
25	Gd	rg	m	f	V				x					
26	G	lg	m	f	V				x	x				
27	G	rg	ms	f/r	I/II				x	x				
28	G	lr	c	n	V				x	x				
29	G	lr	c	f	II/III				x	x				
30	G	rg	mc	ff	I				x	x			x	
31	Gd	drg	s	ff	V					x				
32	Gd	g	s	ff	I/II			x	x					
33	Qd	drg	s	ff	III				x	x				
34	Gd	rg	ms	f	III				x					
35	Gd	g	m	f	II/III				x	x	x			
36	G	r	s	r	III			x						
37	Gd	r	s	ff	V				(x)	x			x	
38	Qd	dr	m	ff	V			x		x			x	+diopside
39	G, Ph	rg	m	f	III	V			x					△ = 0.65 [7]
40	G, Ph	rg	mc	f	I/II	V		(x)	x	x				△ = 0.50
41	Gd, Ph	g	m	f	II	I/II	x	x	x					
42	Gd	lg	m	ff	III				x	x				
43	Gd, Ph	g	mc	f	V	V			x	x				
44	Gd, Ph	g	mc	f	V	V		x	x					
45	Gd	r	mc	ff	V				x					
46	G	g	mc	f	V				x					
47	G	rg	c	f	V				x					

Table 1, contd.

48	G	rg	c	n	V				x	x				
49	Qd	dg	s	ff	IV		x	x	x	x			x	△ = 0.7
50	Gd, Po	g	m	n	I	I/II			x					
51	G	lg	mc	f	I	I			x					
52a	G	lr	c	n	III/V				x					
52b	G	lr	s	n	III				x	x			x	
53	Qd	dr	c	ff/r	I/II			x					x	
54	Gd	lg	m	n	V				x					
55	G	lg	m	ff	V				x	x	x		x	
56	Qd	drg	m	r	II/III			x		x				
57	Gd	g	m	f	V			x	x					
58	Gd	g	m	ff	V				x	x				some granitization
59a	Gd	g	m	f	V			x	x					some granitization
59b	Gd	g	m	ff	V			x	x					
60	Gd	drg	m	f	V			x	x					
61	Gd	g+r	m	ff	V			x	x					some granitization
62	Gd, Po	rg	m	f	V			x	x	x				
63	G	g	m	ff	V			(x)		x			x	
64	Qd	dg	m	f	II		x	(x)	x	x				+diopside
65	Qd	dg	m	n	I/II			x	x	x				
66	G	g	m	n	I				x	x	x			
67	Gd	rg	m	f	II				x	x				
68	G	r	c	f	III					x	x			
69	G	lg	m	f	III				x		x			
70	Gd	g	m	f	I/II				x	x	x			
71	Gd	rg	m	f	II				x	x	(x)			
72	Gd	g	m	f	V				x		x			
73	Gd	rg	m	r	V				x		x			
74	Gd	g	m	ff	V				x		x			
75	Gd	rg	mc	ff	V				x		x			
76	Gd	g	mc	f	V			x	x				x	
77	Gd	g	c	f	V				x				x	
78	Gd	lg	s	f	V				x	x	x			
79	Gd	lg	s	f	III				x	x	x			
80	G	lr	m	n	III				x	x	x			
81	G	r	c	f	IV				x	x	x			
82	Gd	lg	m	n	III				x	x	x			
83	G	r	c	f	II/III				x	x	x			
84	G	lr	c	n	II				x	x	x	x		almost white
85	Gd	g	s	f	V				x					
86	G	g	ms	f	V				x					
87	Gd	g	c	f	IV	IV		x	x					spotted
88	G	g	ms	f	V				x					
89	Gd, Po	g	m	ff	V	V			x					augen gneissose
90	Gd	g	m	ff	V			x	x					
91	Gd	g	m	n	V				x					
92	Gd	g	m	f	III			x	x					
93	G	r	c	f	III/V				x	x	x			
94	G, Po	r	c	n	II/III				x	x	x			
95	G	lg	c	n	I/II				x		x			almost white: +pinite after cordierite
96	G	r	c	n	III				x		x			+pinite+cordierite
97	G	lg	ms	r	II/III					x				
98	G	r	c	n	III/V				x	x	x			+sillimanite+pinite
99	G	lr	s	n	III/V				x	x	x			△ = 0.78
100	G	lr	c	n	V					x	x			△ = 0.75
101	Gd	r	m	r	II				x	x				
102	Gd	rg	mc	ff	III/V				x	x	x			△ = 0.65
103	G	lrg	m	f	V				x	x	x	x		
104	Gd	rg	s	ff	V				x	x	x			
105	Gd, Ph	g	c	n	V	V			x					

Table 1, contd.

106	Gd	g	mc	f	V				x					
107	Gd	dg	ms	r	V				x					
108	Gd, Ph	g	c	f	I/II	I/II	x	x	x					
109	Qd	dg	m	ff	III			x	x	x			x	
110	Gd	g	m	f	I			x	x	(x)	x			
111	Gd	g	m	n	II				x	x				
112	Gd	rg	m	f	I/II			x	x	x				
113	Qd	dg	m	ff	I/II			x	x	x				
114	Gd, Po	g	m	ff		IV			x					
115	Gd	g	m	f	II/III				x	x	x			
116	Gd, Ph	lg	ms	n	V	V			x	x	x			
117	Gd	g	s	f	I/II				x	x	x	x		
118	Gd	rg	m	f	I			x	x	x			x	
119	Qd	rg	c	f	I/II			x	x	x				
120	Gd	dg	c	f		II/III			x	x	x			spotted
121	Gd, Ph	g	m	f	II/III	II			x	x	(x)			
122	Gd, Ph	lg	mc	n	III	III			x	x				
123	Gd	g	m	ff	I/II				x	x	x			
124	Gd	g	m	ff	I/II				x	x	x			
125	Gd, Ph	g	m	f		II			x	x	x			
126	G	gr	c	f	V				x	x	(x)			
127	Gd, Po	g	mc	f		I/II			x	x	x			may be thermometamorphosed by the adjacent Subjotnian diabase
128	G	rg	mc	n	III			x	x					a cross-cutting dike? may be rapakivi
129	Qd	d	m	n	II/III			x	x	x	(x)			greenish; + olivine + clinopyroxene (rapakivi?)
130	Gd	g	m	f	III				x			x		
131	Gd	g	c	f		III			x	x	x	x		spotted
132	Gd, Po	g	mc	ff		III/V			x			x		
133	G	r	c	n	V				x	x	(x)			
134	Pe	r	c	(r)	V						x	x		+ green spinel
135	G	r	m	n	V				(x)	x	x	x		
136	Gd	dg	m	n	V				x	x	x			
137	G	lr	c	n	V				x		x			
138	G	r	m	n	V				x	x	x			
139a	G	r	m	n	I/II				x	x	x			
139b	Pe	r	c	n	II/III	II			(x)	x	x			
140a	G, Po	dr	m	n	II/III				x					100 m from the contact
140b	Gd	rg	s	f	I				x	x	x			300 m from the contact
140c	G	r	c	n	II				x	x	x			500 m from the contact
141	Gd	dg	m	ff	II			x	x	(x)				
142	Gd	g	m	ff	I/II				x					
143	Gd	g	m	f	III		x	x	x	(x)				
144	Gd	g	m	f	IV			x	x					
145	Gd	g	m	n	II/III			x	x		x			
146	Gd	g	m	ff	V			x	x					
147	Gd, Po	g	c	ff	II/III	V			x		x			
148	G, Po	r	c	f	V			(x)	x	(x)				
149	G	r	s	ff	V				x	x	x	x		
150	U, Po	dg+r	m	n	V			x		x			x	reddish albite phenocrysts
151	U	r	c	ff	V					x			x	
152	Gd	lr	c	f	II			x	x	x	x			
153	Gd, Po	g	c	n	II/III	II			x	x	x			

Table 1, contd.

154	Gd	r	c	f	I/II			x	x	x				
155	G		c			III								
156	G	lg	mc	n	II/III				x	x				a cross-cutting dike
157	Gd, Po	g	m	ff		V			x		x			+iddingsite
158	Gd				I									
159a	Gd, Po	g	m	f	IV	V			x	x	x			
159b	Gd, Po	g	m	ff	IV	V		x	x		x			
159c	Gd, Po	r	c	ff		V			x					
160	Gd, Po	g	m	f	I/II	I/II			x	(x)				
161a	Gd, Po	r	c	r	V	V			x	x			x	
161b	Gd, Po	dg	m	r	II	I/II		x	x	x				augen gneissose
162	Gd, Po	g	m	f	I/II				x	x				
163	Gd, Po	g	m	n	I/II				x	(x)				
164	Gd, Po	g	m	ff		I/II		x	x	x				
165a	Gd	dg	mc	f	I/II		x	x	x	(x)				
165b	Gd	dg	m	f	II			x	x	x				
165c	Gd, Po	dg	m	n	I/II	I	x	x	x					
166	Gd	g	s	f	V				x		x			
167	G	r	s	f	III/V				x	x	x			
168	Gd	g	m	f	V				x	(x)				
169	Gd	g	s	ff	V			x	x					
170	Gd, Po	g	m	f	III/V				x	x				△ = 0.54
171a	Gd, Po	g	c	f	I/II	II	x		x					
171b	Gd, Po	g	c	f	II	I		x	x	x				
172	G	r	m	ff	III/V				x					
173	Gd, Po			ff		II								
174	Gd, Po	g	c	ff		II	x		x	(x)				
175	Gd	g	m	ff	II/III				x	x				
176	Gd, Po					II/III								
177	Gd, Po					V			x		x			
178	Gd, Po					II/III								
179	Gd, Po	g	m	r	V	V			x		x			
180	G	g	s	f	III/V				x		x	x		
181	G	g	ms	f	V				x	x	x			
182	Gd, Ph	g	mc	ff	V	V			x	x	x			
183	G	lg	s	f	V				x	x	x			
184	Gd	g	m	ff	I/II				x	(x)	x			
185	Gd, Po	g	m	f		V			x	x	x			
186	Gd, Po	rg	c	f	V	V			x	x	(x)			
187	G	r	m	f	V				x	x	x	x		
188	G	lr	c	n	III/V				x	x	x			a cross-cutting dike
189	G, Po	g	c	f	V					x	x	x		
190	Gd, Po	g	m	f	IV	V			x	x	x			
191	G, Po					II/III								
192	Gd, Po	g	m	f	II	III		x	(x)					+diopside
193	Gd, Po	g	m	f		I/II		(x)	x	(x)				
194	Gd, Po	lr	m	n	II/III	III			x	x				
195	Gd, Po	g	m	n	I/II	I/II	x	(x)	x		(x)			biotite in the state of disintegration
196	Gd, Po	dg	m	f		I/II			x	(x)				
197	Gd, Po	g	m	n	II	I/II			x					
198	Gd, Po	g	m	n	I	I			x		x			
199	Gd, Po	g	m	n	I/II	I/II			x	x			x	
200	Gd	g	m	ff	I/II				x		x			
201	Gd	g	s	n	I/II				x	x	x			
202	Gd	r	s	ff	V				x	x	x			
203	Gd	lg	s	ff	V				x			x		
204	Gd	lr	m	n	V			x	x	(x)				
205	Gd	g	m	f	V			x	x				x	
206	Gd	g	ms	f	V			x	x					
207	G	r	m	f	V				x	x				

Table 1, contd.

208	Gd	lg	mc	n	III/V			x		x		
209	Gd	rg	m	ff	V			x	x		x	granitized
210	G	rg	m	f	V			x	(x)		x	
211	Gd	g	s	ff	IV			x		x	x	
212	Gd, Po	g	c	f		V	x	x	x			
213	Gd	g	m	f	V		x	x		x		
214	G	r	m	n	V			x		x		+cordierite+pinite
215	G	r	m	ff	II/III			x	x	x	x	+pinite (after cordierite)
216	Gd	g	mc	f	II			x		x		
217	Gd, Ph	g	s	f	V	V		x	x	x		
218	Gd	g	m	f	I/II			x	(x)			
219	Gd	g	c	n	I			x	x			+tremolite; calcite-rich
220	Gd	g	c	f	I			x				
221	Gd, Po	g	c	f		I/II	x	x				
222	G	r	m	n	IV			x	x	(x)	x	
223	G	lg	m	ff	IV			x		x		
224	Gd	lg	m	f	V			x				
225	G	r	s	ff	V			x	x			
226	Gd	dg	m	ff	II/III		x	x				
227	Gd	lr	m	f	V		x	x				
228	Qd	dr	s	n	V		x	x	x			
229	Gd	g	ms	ff	V			x				
230	Qd	dg	s	ff	V		x	x	x			
231	Gd	g	m	n	V			x	x			
I	R	r	s	n	III/V							contact variety
II	R	dr	m	n	V	V						contact variety
III	R	r	c	n	V	III						
IV	R	r	c	n	V							
V	R	r	c	n	V							
VI	R	r	c	n	V							
VII	R	r	c	n	II/III							
VIII	R	r	c	n	II							
IX	R	r	c	n	I							
X	R	gr	m	n	II							
XI	R	gr	c	n	II							
XII	R	dr	m	n	I							
XIII	R	dr	s	n	I/II							contact variety

(1) G = granite; Gd = granodiorite; Qd = quartz diorite; Pe = pegmatite granite; U = unakite; R = rapakivi; Po = porphyritic and/or porphyroblastic; Ph = with scattered phenocrysts or porphyroblasts.

(2) g = grey, greyish; r = red, reddish; d = dark, darkish; l = light.

(3) If the rock is porphyritic or porphyroblastic the grain size refers to the matrix. c = coarse grained; m = medium grained; s = small grained.

(4) Foliation as observed in hand specimen: n = massive, i.e., no foliation observed; f = weakly foliated; ff = strongly foliated; r = cataclastic crushing present.

(5) Only recorded if occurring as large flakes; i.e., sericite after feldspar omitted.

(6) x = present; (x) = present in very small quantities. When no thin section available the column is blank.

(7) $\triangle$ = triclinicity of potash feldspar.

Table 1 lists the structural types of both the matrix potash feldspar and the inset potash feldspar. In Plate 1, the structural types I—II are indicated by the orthoclase symbol, structural types II/III—IV by the symbol of randomly disordered potash feldspar and types III/V and V by the microcline symbol. If any deviation occurs between the matrix and the inset potash feldspar, the symbol of matrix potash feldspar is used. Also those few cases in which the triclinicity indicates an intermediate thermal state ($\triangle = 0.4$—0.6) in reflection type V are indicated by the symbol of randomly disordered potash feldspars.

The obliquity, as defined by Goldsmith and Laves (1954), was measured in cases where the potash feldspar was characterized by reflection types IV, III/V and V. Mostly, the obliquity is around 0.9 (from 0.80 to 1.00). Cases where it is less than 0.80 are indicated in Table 1.

The thermal state of the potash feldspars of the matrix and the insets in the same specimen are generally similar. Only in a few cases are there differences.

Width of the aureole

Plate 1 shows the thermometamorphic aureole around the Wiborg rapakivi massif as revealed by the increase in the thermal state of the potash feldspar. The width of the aureole varies considerably. In the northeastern contact zone, it is about 5 kilometers broad (see, however, p. 21). Observations in the field reveal that the contact surface in this area slopes outward. Thus the actual width of the contact aureole as measured perpendicular to the contact surface is less than 5 kilometers. Individual rapakivi granite dikes penetrate the country rock in this area to a distance of 2 to 4 kilometers.

In the west, the contact aureole is similar in width to or slightly narrower than the northeastern aureole. There the contact evidently has quite a steep dip.

Around the satellite massifs — at Suomenniemi, Mäntyharju and Onas —, the orthoclase aureole is considerably narrower than around the main Wiborg massif, being only a few hundred meters broad, or in places it seems to be lacking. Southwest of the Mäntyharju massif, there is an extensive area characterized by potash feldspar in a high thermal state, suggesting the presence of buried rapakivi.

Physical conditions in the aureole

The paragenetic observations concerning the hornfelses indicate high temperatures, possibly exceeding 800°C at the contacts. During the progressive stage, the intergranular pore water was a supercritical aqueous fluid which catalyzed the transformation of microcline into orthoclase. At 1 kb pressure [1]) of H_2O, the transformation temperature presumably is close to 400°C (see, Vorma 1971, pp. 66—67; see

---

[1]) Vorma (1971) assumed the rapakivi granites to have crystallized under the pressure of 1 kb of H_2O.

also Steiger and Hart, 1967, p. 114, for a slightly lower estimate of the transformation temperature).

When the contact metamorphism culminated and the temperature began to drop, the amount and pressure of pore fluid were evidently smaller than during the progressive stage. This also explains why, during the retrograde stage, the transformation of orthoclase into microcline can be expected to take place only in localities where the amount of pore fluid becomes exceptionally large: the aqueous fluid escaped from the rapakivi massif, the greatest part of which solidified during this stage. Taking into account the fact that the rapakivi did not influence the country rock metasomatically, it is evident that the fluid phase escaping from the rapakivi did not percolate evenly through the country rock, in which, owing to the existing high grade of metamorphism, the pore volume was small. Instead, it escaped through larger over-pressure valves and possibly reached the earth's surface.

Relationship between the rapakivi variety and the nature of the potash feldspar in the aureole

Orthoclase is the prevailing potash feldspar in the Wiborg rapakivi granite, although in some large rapakivi masses the potash feldspar is exclusively microcline, as shown by Vorma (1971). These are mainly biotite-bearing rapakivi granites devoid of hornblende and fayalite. They are pyterlites, porphyritic rapakivis, rapakivi granite porphyries, even-grained biotite rapakivis and porphyry aplites and dike rocks. The distribution of these varieties in the Wiborg massif is roughly indicated in the map on Plate 1. Especially in large areas along the northern border zone, the rapakivi consists of varieties rich in microcline.

At first, it seems odd that a rock causing thermometamorphism should contain alkali feldspar in a lower thermal state than the country rock or the rock that was subjected to metamorphism. If the ordering of Al/Si depended only on temperature and the cooling rate, such a situation would be difficult to explain. When the activating role of the supercritical aqueous fluids is also taken into account, the explanation becomes self-evident: the amount of such fluid is surely larger in the cooling intrusive body than in the surrounding non-porous or only slightly porous country rock, especially at the stage when the culmination of the rising temperature in the country rock has been passed and the temperature begins to drop.

Observations of alkali feldspars in the aureole

In thin sections of rocks outside the thermometamorphic aureole, a perfectly sharp microcline twinning is observed in most, if not all, of the specimens. In the aureole, most specimens show grains with no cross-hatching at all; there are also grains with diffuse cross-hatching or patches in grains with marked microcline twinning. In some specimens, furthermore, most of the grains show diffuse or distinct cross-hatching, even though their reflection type indicates a high thermal state. This may be due to the fact that the cross-hatching originated at very low triclinicity values, immediately after the cell symmetry deviated from that of monoclinic orthoclase.

Having undergone a complex thermal history prior to the emplacement of the rapakivi, the alkali feldspars of the plutonic rocks show a highly heterogeneous perthite texture. This heterogeneity is enhanced by the original compositional differences in the alkali feldspars of the plutonic rocks investigated. Some of the alkali feldspars are from quartz diorites, most from granodiorites, either even-grained, porphyritic or porphyroblastic; and the rest from granites that crystallized either from hydrous melts or are a result of granitization. Some of these alkali feldspars are characterized by an irregular vein-perthite texture, some by an irregular patchy perthite texture, and sometimes, especially among those from granites, by a highly developed film-perthite texture besides the irregular vein-perthite texture. The film-perthite texture is often seen in perfectly sharp microcline-twinned alkali feldspar in complete contrast to the rapakivi granite alkali feldspars in which the film-perthite texture is confined exclusively to orthoclase (see, Vorma 1971, p. 37). A well developed plate-perthite texture is sometimes met with in the alkali feldspars of the plutonic country rocks, which is also an indication of the complex thermal history undergone by the rocks. In many a grain the microscopical investigation did not reveal any perthite texture.

No thorough study was made of the differences in perthite texture between the alkali feldspar in and outside the aureole. As a rule of thumb, it may be said that perthite texture is somewhat less clearly developed in the rocks of the contact aureole than outside it. Slight support is obtained from the compositions of the alkali feldspars so far studied (Marmo *et al.* 1963, p. 70). Table 2 shows the albite content in solid solution in the potassic phase of three alkali feldspars from the contact aureole and three from outside it. The figures point to a slight homogenization of the alkali feldspar in the orthoclase aureole. Perhaps the homogenization of the alkali feldspars

TABLE 2

Solid solution of $NaAlSi_3O_8$in potash feldspar of the porphyritic or porphyroblastic granodiorites, northeast of the main Wiborg massif, SE Finland.

Specimen No. (see Table 1)	Triclinicity	$NaAlSi_3O_8$in solid solution in potassic phase (in wt. %)
In the aureole		
197	0.0	6 (G & L)[1], 4 (T & B)[2]
171a	0.0	7 (G & L) , 7 (T & B)
193	0.0—0.20	7 (T & B)
Outside the aureole		
185	0.95—0.97	3 (G & L)
190	0.90—0.95	4 (G & L)
159b	0.94	4 (G & L)

[1] (G&L) refers to the method of Goldsmith and Laves, 1961

[2] (T&B) » » » » » Tuttle and Bowen, 1958

TABLE 3
Optical data of the potash feldspars of the synkinematic porphyritic or porphyroblastic granodiorites, NE contact aureole of the main Wiborg massif, SE Finland.

Specimen No. (see table 1)	$2V\alpha$	$N\gamma \wedge \perp (010)$
In the aureole		
171a	60°—68°	0°
174	44°	0°
165	68°	7°
193	—	0°—10°
156	80°	0°
198	65°	0°
197	62°—65°	0°—5°
Outside the aureole		
181	76°—86°	18°
177	74°	15°

was more complete during the culmination of the thermometamorphism but was followed by subsequent exsolution. Grains with well developed film perthite, in addition to the irregular perthite texture, as mentioned in the foregoing, support this assumption.

Table 3 is a compilation of *U*-stage data published by Marmo and others (1963, p.74) on seven potash feldspar insets of plutonic rocks from the contact aureole and on two from outside it. Again, the same general tendency is to be found: in the contact aureole, the axial angles are low, while farther away $2V\alpha$ increases.

The axial angles vary from —44° to that characteristic of a maximum microcline. The orthoclase in specimen 174 has $2V\alpha = 44°$. This specimen was taken from a distance of a few meters from the rapakivi granite contact. Specimen No. 156 represents an even-grained granite that genetically may be classified as a synkinematic granodiorite. The feldspar is orthoclase microperthite; both the extinction angle and the triclinicity determined by the X-ray powder method indicate orthoclase. The value of the axial angle, $2V\alpha = 80°$, however, could be explained if the potash feldspar is assumed to be a submicroscopically and sub-X-ray twinned microcline. All the potash feldspars listed in Table 3, with $2V\alpha$ close to 60°—65° and with a straight extinction, might be submicroscopically twinned as well, because the individual lamellae have structural states that fall between an orthoclase an a maximum microcline.

Notes on the behavior of other minerals of plutonic rocks in the aureole

Cummingtonite

Cummingtonite is of special interest for this study. Most of the cummingtonite-bearing granodiorites of the area so far investigated contain potash feldspar in a high thermal state, as determined by X-ray powder methods. Most of the cummingtonite-bearing specimens are from the northeastern contact area. Specimens 108, 41 and 49 are from the area to the west of the Wiborg massif, outside the contact area. To some extent, the cummingtonite seems to be a pseudomorph after orthopyroxene, which would imply quite dry conditions of crytallization for granodiorite; but a primary origin is also possible. Invariably coexisting with cummingtonite is green hornblende, derived from cummingtonite, at least partly, by a reaction between the anorthite component of the plagioclase and the cummingtonite.

Notice should be taken of the fact that the biotite in cummingtonite-bearing granodiorites is only exceptionally chloritized and that the rock is lacking in muscovite. On the other hand, in some of the specimens biotite has a distinct reddish-brown color, indicating, according to Hayama's (1959) studies, high TiO_2 contents, an indication of high crystallization temperature.

It is assumed that the cummingtonite predates the emplacement of the rapakivi because cummingtonite is quite a common mineral in amphibolites and gabbros outside the contact aureole. Thus the existence of an orthoclase »zone» older than the rapakivi emplacement is to be expected in the area, which later became the northeastern contact aureole of the rapakivi. Accordingly, the contact aureole proper there might be somewhat narrower than shown in the map in Plate 1 (see also p. 17).

Hornblende

The data in Table 1 suggest that the hornblende-bearing granodiorites and quartzdiorites outside the contact aureole contain potash feldspar in lower thermal states than the biotite granodiorites do. The behavior of the hornblende near the contact line and its assumed compositional changes caused by thermometamorphism await future studies. In some cases, near the contacts, the hornblende shows bluish hues, which point to possible alkali enrichment.

In some of the rocks, the hornblende has altered, producing minerals of the epidote group, and the biotite has chloritized. In certain other rocks, the hornblende was only bleached while some epidote was produced. The rock of specimen No. 118 was subjected to this kind of retrograde metamorphism. Its potash feldspar is mainly orthoclase and the specimen is from the thermometamorphic contact aureole. If the retrograde reactions predate the rapakivi emplacement, then the temperature of the rock during the contact metamorphism presumably was somewhere between 400° and 600°C (see, e.g., Turner 1968, p. 154). Another possibility is that the retrograde reactions that led to the epidotization of the amphibole took place after the culmination of the thermometamorphism, orthoclase being left as a relict.

Biotite

The data available on biotite do not justify its use as an indicator of thermometamorphism around the Wiborg massif. Chloritization is a common feature of biotite.

In granitic rocks, it often is quite far advanced, in granodiorites usually not so far. Between hornblende-bearing and hornblende-free granodiorites, no distinction can be made in this respect. Both varieties show biotite with varying chloritization (see the cummingtonite-bearing varieties in the foregoing). In the author's opinion, most if not all of the chloritization of the biotite, also in the contact aureole, took place before the emplacement of the rapakivi.

NOTES ON THE DEFORMATION OF THE COUNTRY ROCK OF THE RAPAKIVI

The different contact phenomena, e.g., chilled margins, contact breccias and banded marginal modifications caused by the flow of magma (see, e.g., Vorma 1965), point to a disharmonic intrusion. The contacts cut across all the structures of the Svecofennidic belt. Around the Wiborg rapakivi massif, arterites produced by rapakivi are either extremely rare or completely lacking. The country rock presumably never began to melt and never became mobile. The Svecofennidic rocks were subjected only to epeirogenic movements and fracturing during the emplacement of the rapakivi granite. The intrusions forced their way by stoping and intrusive faulting.

The diabase dikes, which are older than the rapakivi but evidently Subjotnian in age, are related to the Häme diabase dike set in southern Finland (Laitakari 1969), and they cut rectilinearly the Svecofennidic structures. As far as the author knows, these dikes show no signs near the rapakivi of plastic deformation during the emplacement of the rapakivi. Their trend is constant, westerly to northwesterly. Thus most of the plastic deformation of the country rock predates the intrusion of the rapakivi.

DISCUSSION

Around both the synkinematic and late-kinematic deep-seated plutonic rocks, the contact aureole is indistinct. The thermal gradient induced was low during their emplacement, the cooling rate sluggish and the volatile pressure mostly in equilibrium in both the plutonic and regionally metamorphosed rocks. The thermal state of the potash feldspar was controlled by the metamorphic facies involved:

- in a dry milieu, e.g., under the conditions of granulite facies and the upper part of amphibolite facies, orthoclase is produced (Eskola 1952, 1957; Heier 1957; Sedova and Kotov 1970),
- in a milieu richer in volatiles, e.g., under the conditions of amphibolite facies, lower thermal states usually prevail in potash feldspar (Heier 1957, Sedova and Kotov 1970).

Budding (1968) described potash feldspar occurring in Precambrian metasediments in the Västervik area in southeastern Sweden which were metamorphosed under the conditions of regional metamorphism in the upper part of the amphibolite facies. This potash feldspar shows zero to low obliquity. The metasediments are penetrated by late-kinematic granites. In the immediate exocontact zone, the orthoclase has inverted to microcline. Budding attributes this change to granitic emanations. The granite itself has potash feldspar in a low thermal state. Budding concludes that recrystallization and solid state reactions in the granitic rocks had taken place at lower temperatures than in the metasediments; this reflects the higher water content of the granitic melt, which was probably water-saturated during much of its crystallization history. He points out, however, that the scarcity of volatiles in the metamorphic rocks may have prevented further ordering.

Zones of orthoclase around shallow intrusions have been described from several localities. Mostly the intrusions are postorogenic. Eskola (1951) described a pronounced orthoclase province, a couple of kilometers across, connected with the western contact aureole of the Salmi rapakivi granite massif, northeast of Lake Ladoga. In his general description of the rapakivi granites in Finland, Väyrynen (1954, p. 93) noted that usually the influence of rapakivi on the country rock is very slight; only the microcline in granitic country rocks is inverted into orthoclase. Kornfält (1969) described the thermometamorphic contact aureole around the Subjotnian Ragunda rapakivi massif in Sweden. The aureole measures in places a few kilometers across, and it is characterized by orthoclase transformed from microcline.

Marked orthoclase development is not confined to rapakivi alone. Heier (1957, p. 477) and Rao (1960) discussed the contact metamorphism produced by the Permian igneous (subvolcanic) rocks in the Precambrian gneisses of the Oslo region. Close to the contact, the potash feldspar is of a markedly higher thermal state than that farther from the contact. According to Rao, the zone containing disordered potash feldspars is only a few tens of meters wide.

The Tertiary Eldora quartz-monzonite stock in Colorado is a shallow intrusion that converted the microcline perthite of Precambrian pegmatites into orthoclase (Steiger and Hart 1967). The pronounced orthoclase zone is from 600 to less than 2 900 feet across. Shimazu (1962) described orthoclase in the high-grade zone of the contact-metamorphic aureole around the Cretaceous Tanohata granitic mass, a shallow intrusion in Kitakami Mountainland, Japan. According to Shimazu (*op.cit.*, p. 233), these contact-metamorphic rocks formed under much lower rock pressure than those of the central Abukuma type. The Donegal granites in Ireland intruded into an epizonal assemblage of folded sedimentary rocks of Dalradian age during a late episode in the Caledonian revolution (Pitcher and Read 1963). Hall (1966) showed that the higher thermal state in the potash feldspar at the eastern end of the Ardara pluton, Donegal, is very probably related to the subsequent intrusion of the main Donegal granite.

Tilling (1968) described the alkali feldspars of the granodioritic Rader Creek pluton, emplaced at a relatively shallow depth, within the Cretaceous composite Boulder batholith in southwestern Montana. Tilling's study suggests that exsolution and partial inversion of orthoclase into intermediate microcline took place during the cooling of the Rader Creek pluton and, subsequently, the intermediate microcline assemblage transformed into orthoclase during reheating brought about by the intrusion of younger plutons within the batholith.

Late-kinematic granites, dated 930 m.y. (Smithson 1963, p. 177) penetrate Precambrian metamorphosed (upper catazonal) supracrustal rocks in the Flå and Bamble-Telemark areas, southern Norway. The low and/or variable obliquity of the potash feldspars in the augen gneisses occurring near the contact of the Flå granites (Smithson, *op.cit.*) has been attributed to the intrusion of the granites mentioned. No continuous orthoclase zone can, however, be found around the granites. Migmatization of the country rocks is more pronounced there than around the Subjotnian rapakivi granites in Finland. Evidently this difference is due to the much deeper burial of the Flå granites than that of the rapakivi massifs. The same applies to the Herefoss granitic pluton, studied by Nilssen and Smithson (1965). The potash feldspars in the country rocks belonging to the Telemark gneisses exhibit low, variable and some high triclinicity values.

In most of the examples cited, the authors have regarded the volatiles to be the major cause in regulating the order-disorder relations in potash feldspars. All the examples, the aureole around the Wiborg rapakivi granite included, prove that the potash feldspar can be used as a tool in mapping the thermometamorphic contact aureoles, provided that the study is based, however, on a sufficiently large number of specimens.

In addition to their use in the estimation of the depth of emplacement of a granitic mass and of the thermal gradient around it, in favourable circumstances potash feldspars give information on the age relations of different intrusive phases within a composite pluton. It has not been possible, for example, to establish by field methods alone the age relation of the Suomenniemi satellite massif (Plate 1) to the main Wiborg massif (see also Vorma 1971, p. 7). The potash feldspars open a new approach to the problem.

The Suomenniemi massif shows chilled margins against non-rapakivitic country rocks. Hornblende rapakivi grades over to a granite porphyritic variety with a fine-grained groundmass. Chilled margins are also seen along the southern contact zone, where it is located inside the orthoclase zone, about 5 km broad, around the main rapakivi massif. Had the Suomenniemi granite intruded slightly after the emplacement of the main massif, chilled margins would not have been produced in rocks warmed up by the heat emanating from the main massif. The assumption involving the precedence of the emplacement of Suomenniemi granite in respect to the main Wiborg rapakivi receives support also from the nature of the alkali feldspars contained in the Suomenniemi granite. Although scattered, the data indicate that its potash feldspar is microcline. In the rocks adjacent to the contact line (not exposed) against the main Wiborg rapakivi, orthoclase is the prevailing potash feldspar. The microcline in the southeastern margin of the Suomenniemi rapakivi seems to have been transformed into orthoclase by the heat generated by the main rapakivi. This would indicate between the intrusion of the Suomenniemi massif and the main Wiborg massif a time gap of such a length that the Suomenniemi massif had cooled down at least to 400°C before the intrusion of the main Wiborg rapakivi granite took place.

The contact aureoles of the satellite massifs of Suomenniemi, Mäntyharju and Onas are much narrower than the aureole around the main Wiborg massif. It is thus highly likely that the satellite massifs represent intrusions truly separate from the main Wiborg massif. Were the non-rapakivitic granite area between the Suomenniemi and Mäntyharju massifs merely a thin roof topping a combined Wiborg—Suomenniemi—Mäntyharju massif, as supposed on the basis the gravity data reported by Laurén (1970), there would be no apparent reason for the diversity of contact aureoles around the different »cupolas».

The interpretation of the development of the thermometamorphic aureole and the thermal behavior of alkali feldspar opens a possibility to evaluate the age relations of the different granitic dikes that occur in the aureole. A cross-cutting granite dike, 0.2—1 m broad, at Sarviniemi, Lappeenranta (see, Vorma 1965, p. 37), may serve as an example. It is situated about 700 m away from the contact of the Wiborg massif. It bears maximum-microcline, as do most of the rapakivi dike rocks (Vorma 1971). The orthoclase zone in the Lappeenranta area is about 5 km broad (see, Plate 1). In the terrain, no proof was found to show the dike to have originated from rapakivi, but the potash feldspar relations strongly point to the rapakivitic origin of this dike. As a matter of fact, the dike rock in question contains plenty of fluorite and zircon as accessory minerals, both characteristic of the rapakivi suite. Thus it seems possible to distinguish the rapakivitic dikes, at least the youngest of them, from the Svecofennidic dike rocks in the thermometamorphic aureole. The latter underwent thermometamorphism, whereby their microcline inverted into orthoclase. In contrast, the rapakivitic dikes crystallized from silicate melts rich in volatiles. At submagmatic temperatures, the volatile pressure in the dikes was high enough to catalyze the inversion of the orthoclase into microcline. In the country rock, the volatile pressure was lower and no transformation took place in the potash feldspar along with decreasing temperature.

REFERENCES

Budding, A. J. (1968) Alkali feldspars from gneisses and granites of the Västervik area, SE. Sweden. Geol. För. Stockholm Förh., Vol. 90, pp. 504—518.

Buddington, A. F. (1959) Granite emplacement with special reference to North America. Bull. Geol. Soc. America, Vol. 70, pp. 671—747.

Eskola, Pentti (1951) Around Pitkäranta. Ann. Acad. Scient. Fennicæ, Ser. A, III, 27. 90 p.

—»— (1952) On the granulites of Lapland. Amer. J. Sci., Bowen Volume, pp. 133—171.

—»— (1957) On the mineral facies of charnockites. J. Madras Univ., B. 27, pp. 101—119.

Goldsmith, Julian R. and Laves, Fritz (1961) The sodium content of microclines and the microcline-albite series. Feldspar-symposium. Cursillos y Conferencias, Instituto »Lucas Mallada», Madrid, Fasc. VIII, pp. 81—95.

Hackman, Victor (1934) Das Rapakiwirandgebiet der Gegend von Lappeenranta (Willmanstrand). Bull. Comm. Géol. Finlande 106. 87 p.

Hall, A. (1966) The alkali feldspars of the Ardara pluton, Donegal. Mineral. Mag., Vol. 35, pp. 693—703.

Härme, Maunu (1965) On the potassium migmatites of southern Finland. Bull. Comm. Géol. Finlande 219. 43 p.

Hayama, Yoshikazu (1959) Some considerations on the color of biotite and its relation to metamorphism. J. Geol. Soc. Japan, Vol. 65, pp. 21—30.

Heier, K. S. (1957) Phase relations of potash feldspar in metamorphism. J. Geol., Vol. 65, pp. 468—479.

Jahns, Richard H. and Burnham, C. Wayne (1969) Experimental studies of pegmatite genesis, I. A model for the derivation and crystallization of granitic pegmatites. Econ. Geol., Vol. 64, pp. 843—864.

Kornfält, Karl-Axel (1969) X-ray and optical observations on the K-feldspars from the Ragunda area, Central Sweden. Sveriges Geol. Unders., Ser. C, Nr. 636; Årsbok 62. 33 p.

Kouvo, Olavi (1958) Radioactive ages of some Finnish pre-Cambrian minerals. Bull. Comm. Géol. Finlande 182. 70 p.

Kouvo, Olavi and Simonen, Ahti (1967) Tectonic units and geochronology of the Baltic Shield. Abstracts of papers from a conference held at the Department of Geology, University of Alberta, pp. 55—56.

Laitakari, Ilkka (1969) On the set of olivine diabase dikes in Häme, Finland. Bull. Comm. Géol. Finlande 241. 65 p.

Laitakari, Ilkka and Simonen, Ahti (1962) [Map of] Pre-Quaternary rocks, sheet 3022, Lapinjärvi. Geological Map of Finland, 1 : 100 000.

Laitala, Matti (1964) [Map of] Pre-Quaternary rocks, sheet 3021, Porvoo. Geological Map of Finland, 1 : 100 000.

—»— (1965) [Map of] Pre-Quaternary rocks, sheet 3012, Pellinki. Geological Map of Finland, 1 : 100 000.

Laurén, Lennart (1970) An interpratation of the negative gravity anomalies associated with the rapakivi granites and the Jotnian sandstone in southern Finland. Geol. För. Stockholm Förh., Vol. 92, pp. 21—34.

Laves, Fritz (1950) The lattice and twinning of microcline and other potash feldspars. J. Geol., Vol. 58, pp. 548—571.

Lehijärvi, Mauno (1964) [Map of] Pre-Quaternary Rocks, sheet 3111, Lahti. Geological Map of Finland, 1 : 100 000.

—»— (1964) Kallioperäkartan selitys, lehti 3111, Lahti. Summary: Explanation to the map of rocks. Suomen geologinen kartta, 1 : 100 000.

—»— (1970) [Map of] Pre-Quaternary rocks, sheet 3112, Heinola. Geological map of Finland, 1 : 100 000.

Lehijärvi, Mauno and Tyrväinen, Aimo (1969) [Map of] Pre-Quaternary rocks, sheet 3114, Vuohijärvi. Geological Map of Finland, 1 : 100 000.

Marmo, Vladi (1967a) On granites; a revised study. Bull. Comm. Géol. Finlande 227. 83 p.

—»— (1967b) On the granite problem. Earth-Sci. Rev., Vol. 3, pp. 7—29.

Marmo, Vladi, Hytönen, Kai and Vorma, Atso (1963) On the occurrence of potash feldspar of inferior triclinicity within the Precambrian rocks in Finland. Bull. Comm. Géol. Finlande 212, pp. 51—78.

Matisto, Arvo (1962) Ortoklaasipitoisista porfyyrisistä granodioriiteista. English summary: On some orthoclase-bearing porphyritic granodiorites. Geologi, Vol. 14, pp. 118—121 (Helsinki).

Meriläinen, Kauko (1966) [Map of] Pre-Quaternary rocks, sheet 4112+4111, Imatra. Geological Map of Finland, 1 : 100 000.

Nilssen, Borghild and Smithson, Scott B. (1965) Studies of the Precambrian Herefoss granite, I. K-feldspar obliquity. Norsk Geol. Tidsskr., Bd 45, pp. 367—396.

Pitcher, W. S. and Read, H. H. (1963) Contact metamorphism in relation to manner of emplacement of the granites of Donegal, Ireland. J. Geol., Vol. 71, pp. 261—296.

Rao S. V. Lakshmi Narayana (1960) X-ray study of potash feldspar of the contact metamorphic zones at Gjelleråsen, Oslo. Norsk Geol. Tidsskr., Bd. 40, pp. 1—12.

Savolahti, Antti (1956) The Ahvenisto massif in Finland. Bull. Comm. Géol. Finlande 174. 96 p.

—»— (1962) The rapakivi problem and the rules of idiomorphism in minerals. Bull. Comm. Géol. Finlande 204, pp. 33—111.

Sederholm, J. J. (1926) On migmatites and associated pre-Cambrian rocks of southwestern Finland, Part II. The region around the Barösundsfjärd W. of Helsingfors and neighbouring areas. Bull. Comm. Géol. Finlande 77. 143 p.

—»— (1932) On the geology of Fennoscandia. Bull. Comm. Géol. Finlande 98. 30 p.

Sedova, I. S. and Kotov, N. V. (1970)

Седова, И. С., Котов, Н. В. (1970) Фазовые превращения калиевых шпатов гранито-гнейсов и гранитоидов в процессах деформаций пород при прогрессивном и наложенном региональном метаморфизме. В сб.: Региональный метаморфизм и метаморфогенное рудообразование. Институт геологии и геохронологии докембрия, АН СССР. Изд. ''Наука'', Ленинград. Стр. 52-67.

Shimazu, Mitsuo (1962) Petrological study of the thermally metamorphosed rocks surrounding the Tanohata granitic mass, northern Kitakami Mountainland, northeastern Japan (II). J. Japan. Assn. Min. Petr. and Econ. Geol., Vol. 48, pp. 220—234.

Simonen, Ahti (1960) Plutonic rocks of the Svecofennides in Finland. Bull. Comm. Géol. Finlande 189. 101 p.

—»— (1961) Feldspar-equilibrium temperature of some Finnish rocks. Bull. Comm. Géol. Finlande 196, pp. 367—370.

—»— (1965) [Map of] Pre-Quaternary rocks, sheet 3024, Karhula. Geological Map of Finland, 1 : 100 000.

Simonen, Ahti and Laitala, Matti (1970) [Map of] Pre-Quaternary rocks, sheet 3032+3014, Kotka. Geological Map of Finland, 1 : 100 000.

Simonen, Ahti and Lehijärvi, Mauno (1963) [Map of] Pre-Quaternary rocks, sheet 3113, Kouvola. Geological Map of Finland, 1 : 100 000.

Simonen, Ahti and Tyrväinen, Aimo (1965) [Map of] Pre-Quaternary rocks, sheet 3132, Savitaipale. Geological Map of Finland, 1 : 100 000.

Simonen, Ahti and Vorma, Atso (1969) Amphibole and biotite from rapakivi. Bull. Comm. Géol. Finlande 238. 28 p.

Smithson, Scott B. (1963) Granite studies, II. The Precambrian Flå granite, a geological and geophysical investigation. Norges Geol. Unders., Nr. 219. 212 p.

Steiger, Rudolf H. and Hart, Stanley R. (1967) The microcline-orthoclase transition within a contact aureole. Amer. Mineral., Vol. 52, pp. 87—116.

Sviridenko, L. P. (1968)

Свириденко, Л. П. (1968) Петрология Салминского массива гранитов рапакиви (в Карелии). Труды Инст. геол. Карельск. филиала АН СССР, вып. 3. 115 стр.

Tilling, Robert I. (1968) Zonal distribution of variations in structural state of alkali feldspar within the Rader Creek Pluton, Boulder Batholith, Montana. J. Petr., Vol. 9, pp. 331—357.

Turner, Francis J. (1968) Metamorphic petrology: Mineralogical and field aspects. McGraw-Hill Book Company, New York.

Tuttle, O. F. and Bowen, N. L. (1958) Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O. Geol. Soc. Amer., Memoir 74. 153 p.

Väyrynen, Heikki (1954) Suomen kallioperä. Otava, Helsinki.

Vorma, Atso (1964) [Map of] Pre-Quaternary rocks, sheet 3134, Lappeenranta. Geological Map of Finland, 1 : 100 000.

—»— (1965) Kallioperäkartan selitys. Lehti 3134, Lappeenranta. Summary: Explanation to the map of rocks. Suomen geologinen kartta, 1 : 100 000.

—»— (1971) Alkali feldspars of the Wiborg rapakivi massif in southeastern Finland. Bull. Comm. Géol. Finlande 246. 72 p.

Winkler, H. G. F. (1967) Petrogenesis of metamorphic rocks. Springer-Verlag, New York.

Yletyinen, Veijo (1952) Koskenkylän liuskealueen geologiasta [On the geology of the Koskenkylä schist area]. Manuscript, Department of Geology and Mineralogy, University of Helsinki.

ACKNOWLEDGMENTS

The author wishes to acknowledge his gratitude to colleagues and co-workers at the Geological Survey of Finland.

This work would have remained only half done without stimulating discussions with my superior, Professor Ahti Simonen, and my colleagues Dr. Mauno Lehijärvi and Mr. Matti Laitala.

Mrs. Mirja Saarinen did a fine job in separating the potash feldspars as well as in performing all the X-ray runs. Mrs. Elsa Järvimäki drew the map reproduced in Plate 1. The thin sections were prepared by Mr. Raimo Aromaa. Several specimens were received for this study from the compilers of the geological map sheets covering the surroundings of the Wiborg massif, viz., Professor Ahti Simonen, Drs. Ilkka Laitakari, Mauno Lehijärvi and Kauko Meriläinen, and Messrs Matti Laitala and Aimo Tyrväinen. Messrs Seppo Aaltonen and Kari Vuorio collected a substantial part of the specimens. For all this, the author wishes to express his appreciation.

Professor Ahti Simonen and Dr. Kai Hytönen read the manuscript critically. Dr. Marjatta Okko's editorial reading of the manuscript is likewise gratefully acknowledged.

Manuscript received November 15, 1971.
Revised manuscript received December 14, 1971.

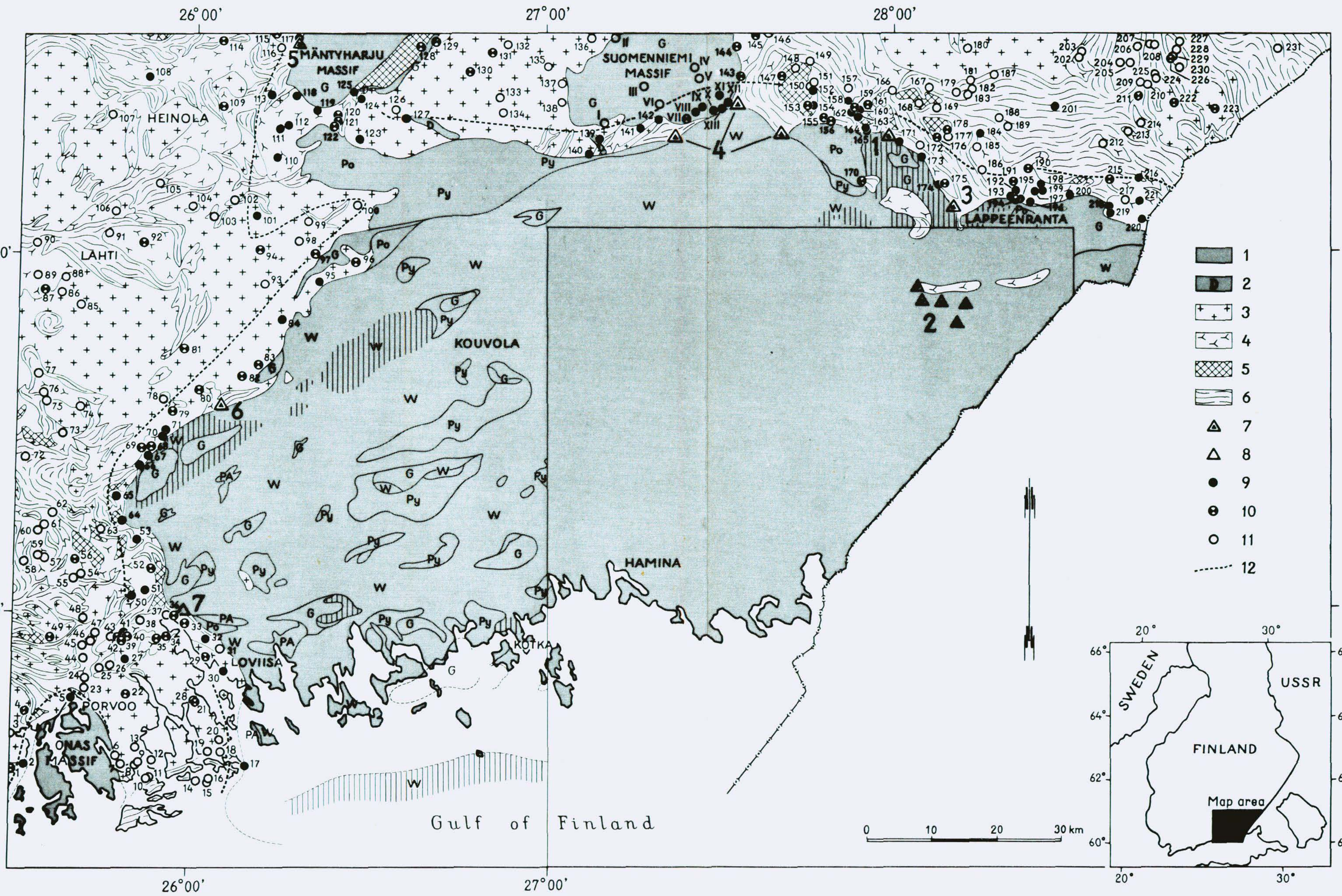
Finnish part of the Wiborg rapakivi granite massif and its surroundings

1 Rapakivi granite
  - W wiborgite
  - Py pyterlite
  - Po porphyritic rapakivi
  - G even-grained rapakivi
  - PA porphyry aplite
  - vertical striation
    - dark and darkish rapakivi granite

2 Subjotnian diabase
3 Svecofennidic granites
4 Svecofennidic granodiorites
5 Svecofennidic basic plutonic rocks
6 Svecofennidic supracrustal rocks
7 hypersthene hornfels
8 albite-epidote hornfels
9 orthoclase
10 randomly disordered potash feldspar
11 microcline
12 tentative outer border of thermometamorphic aureole as revealed by the increase of thermal state in potash feldspar

The map was generalized by Mrs. Elsa Järvimäki from the petrological map quadrangles, scale 1 : 100 000, compiled by

Laitakari and Simonen 1962
Simonen and Lehijärvi 1963
Laitala 1964 and 1965
Lehijärvi 1964 and 1970
Vorma 1964
Simonen 1965
Simonen and Tyrväinen 1965
Meriläinen 1966
Lehijärvi and Tyrväinen 1969
Simonen and Laitala 1970



Atso Vorma: On the contact aureole of the Wiborg rapakivi granite massif in southeastern Finland

ISBN 951-690-000-3