

## ON MINERALOGY OF THE PORPHYRACEOUS POTASSIUM GRANITES OF SMALL MASSIFS IN THE NORTHERN ESTONIAN BASEMENT

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**Abstract.** The content of porphyreous potassium granites and the chemical composition of these minerals bear witness to a remarkable heterogeneity of small plutons and also to the process of their evolution through many stages. An attempt was made to define the conditions of the formation of potassium granites and the possible cooling rate of plutons. Basing on the zircon types it is possible to distinguish early- and late-magmatic stages in the massifs.

**Key words:** mineralogy, potassium granites, Precambrian, Estonia.

### INTRODUCTION

Presently five small early platform massifs of porphyreous granites are known in North Estonia. These are Märjamaa, Naissaare, Neeme, Taebala, and Ereda (Soesoo & Niin, 1992; Fig. 1). They are genetically and by age related to Wiborg and Riga rapakivi plutons. According to the geophysical data, the massifs of potassium granites of North Estonia occur as intrusions sharply transecting the surrounding lower Proterozoic metamorphic rocks. We compared these massifs with the small ones of South Finland (Кууспалу, 1975).

The biggest, Märjamaa massif (40×25 km), has an asymmetrically rounded form (Fig. 1a) and zonal composition. The central part of the pluton consists of relatively melanocratic rock (Table 1) whose mineralogical and chemical composition is close to granodiorite. It was probably formed at the earliest stage of the intrusion process (representing the first phase of crystallization). The periphery of the massif is made up of more leucocratic granites (second phase) with increased content of microcline and decreased content of biotite. The oval-shaped northwestern part

of the massif, forming the so-called gravity minimum of Kloostri, differs substantially from its main part. Here the most leucocratic granites were formed at the last stage of the intrusion (third phase). Unlike the main rocks of the massif, the granites of the third phase do not contain hornblende, but the appearance of muscovite and fluorite is typical, and so is the sporadic trachytoid structure.

The northern part of the Naissaare massif (35×25 km, Fig. 1b) lies under the Gulf of Finland. The most melanocratic granites (first phase) form the periphery of the massif. The central part of the pluton is composed of leucocratic granites (second phase), which have some similarities with the third phase of the Märjamaa intrusion.

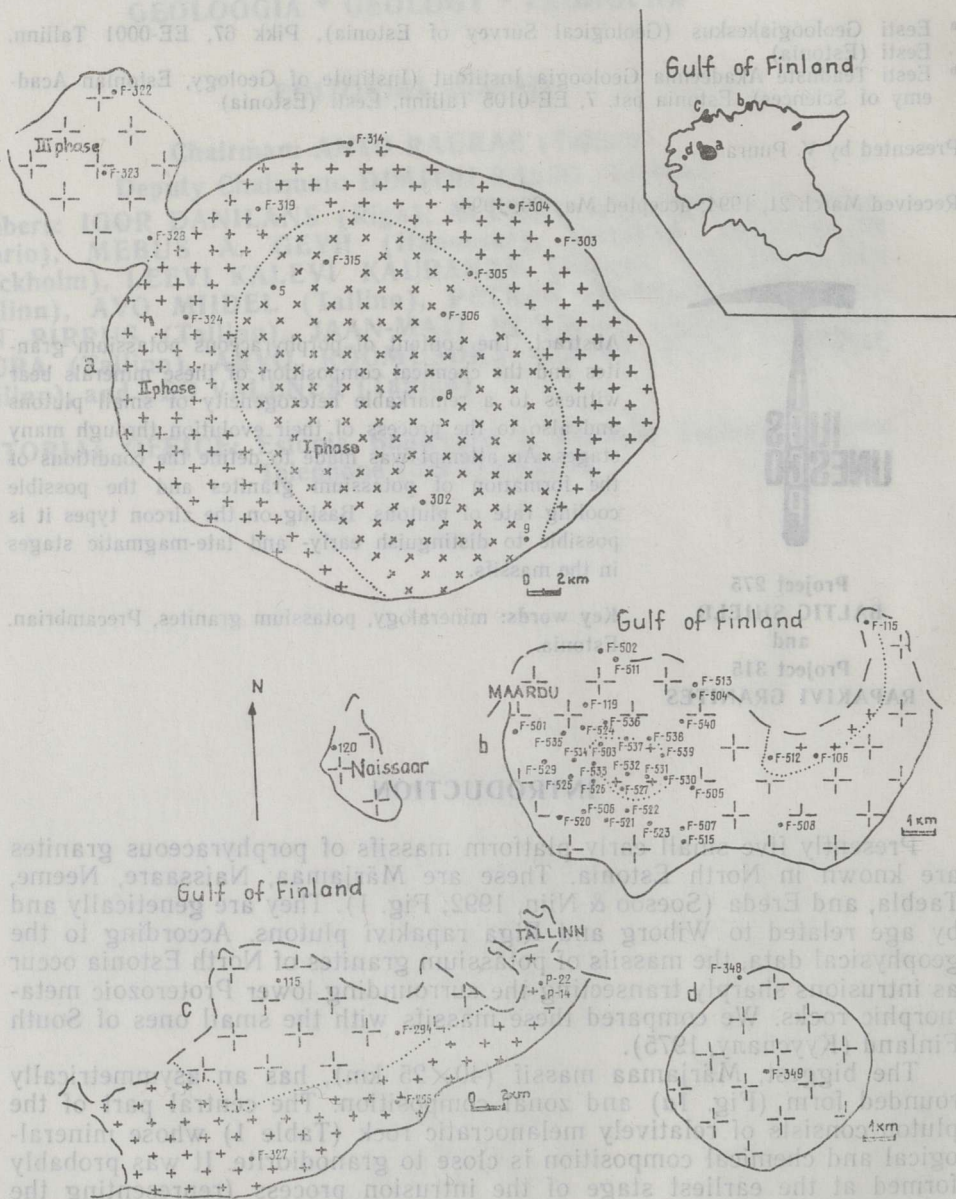


Fig. 1. Location and size of the studied porphyreous potassium granite massifs. Dots with numbers designate drill holes. a, Märjamaa; b, Neeme; c, Naissaare; d, Taebila.



Table 1

Mineral composition of porphyreous potassium granites  
(average modal composition, vol. %)

Minerals	Plutons/phases							
	Märjamaa			Neeme		Nai- saare	Taebla	Aplites
	I	II	III	I	II			
Quartz	25.8	25.6	27.8	34.8	28.3	28.3	28.0	31.3
Microcline	23.1	49.0	34.0	23.1	38.6	31.0	39.3	31.6
Plagioclase	37.8	17.1	34.3	33.4	28.1	32.2	25.0	31.6
Biotite	7.0	3.4	2.1	7.8	3.9	6.6	5.6	4.8
Muscovite	—	+	+	0.1	0.3	—	1.0	0.2
Hornblende	2.9	4.0	—	0.2	—	1.7	—	—
Opaques	1.5	0.7	1.1	0.3	0.6	+	0.3	0.5
Accessories	1.9	0.2	0.7	0.3	0.2	0.2	0.8	+
Total	100	100	100	100	100	100	100	100

+ a few grains; — not found.

The Neeme massif (diameter *c.* 15 km, Fig. 1c), like the Naissaare massif, lies partly under the Gulf of Finland. By its chemical and mineralogical composition this pluton can be divided into two phases. Two small central zones consist of more melanocratic granites (first phase), the main part of the massif is composed of leucocratic granites (second phase) similar to the most leucocratic varieties of Märjamaa and Naissaare granites (Table 1).

The Taebla massif is the smallest with a diameter of 6—7 km (Fig. 1d). The leucocratic granites of the pluton are rather homogeneous and similar to the rocks of the third phase of the Märjamaa massif and the second phases of the Neeme and Naissaare massifs.

The Ereda massif (15×5 km), oval in form, is composed of homogeneous porphyreous granites. As the material available from two drill cores is limited, it is complicated to correlate these rocks with others. However, some similarities have been observed between the Ereda granites and more leucocratic types of the Märjamaa, Neeme, and Naissaare granites.

## METHODS

Geological characterization of the potassium granites was compiled and examination of mineralogical composition of the rocks was carried out by Mati Niin. Heavy mineral fractionation was studied and the description of accessory minerals was presented by Mare Kõnša. The minerals were separated and the analyses interpreted by Vello Klein.

Heavy mineral grains (accessories and opaques) were studied by means of immersion-microscopic analysis. The number of grains counted from each sample was 500. This method is less exact than the crystallo-optical method (Вийдинг, 1976), but it enables to operate with rather small samples and is well applicable for the comparison of similar rock types (Клейн & Кõнса, 1986).

Wet chemical analyses of minerals were carried out at the Chemical Laboratory of the Geological Survey of Estonia by Mare Kalkun and Silvi Hinn.

## MINERAL COMPOSITION

Quartz, plagioclase, microcline, and biotite are the dominant minerals in porphyreous potassium granites of all petrographic varieties (Table 1). Macroscopically separated distinct phases of massifs display differences in the content of these minerals; some phases include in addition hornblende and muscovite. Hornblende is rather frequent in the Märjamaa granites of phases I and II and in the Naissaare granites, but less frequent in the Neeme granites of phase I.

Muscovite characterizes usually the latest phase of granite crystallization or occurs as a secondary mineral. The content of the opaques and accessories is rather small exceeding the average of 1% only in phase I of the Märjamaa massif. A characterization of whole-rock minerals can be found in an earlier publication (Soesoo & Niin, 1992).

According to microcline/quartz/plagioclase ratios the composition of phase I of the Märjamaa granites and the Neeme granites is close to that of granodiorite (Fig. 2).

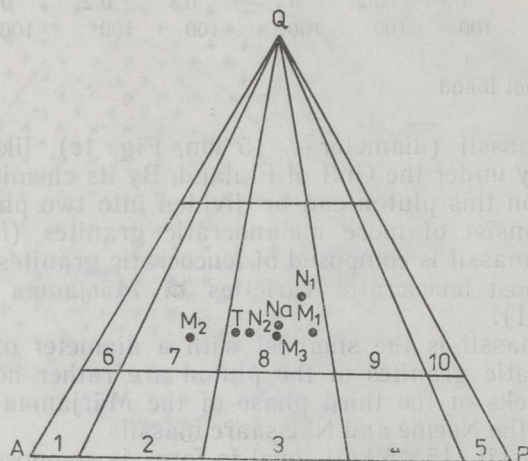


Fig. 2. Average modal composition of the granites shown in the APQ diagram of Streckeisen (1974).

M<sub>1</sub>, M<sub>2</sub>, M<sub>3</sub>, Märjamaa; N<sub>1</sub>, N<sub>2</sub>, Neeme; Na, Naissaare; T, Taebla granites.

## CHEMICAL COMPOSITION OF MINERALS

The chemical composition of rock-forming minerals was examined by wet chemical analysis of 13 biotite and 3 hornblende samples (Tables 2 and 3). The general aspects of the evolution of the granitic magma in the studied massifs were discussed by Kirs and Soesoo on a more representative material earlier (Kupc et al., 1990; Soesoo, 1993). Their discussion gives a wider background for the interpretation of the chemical analyses of the selected samples carried out for getting approximate estimates of mineral crystallization conditions and the speed of the processes involved.

The analyses revealed that the iron and titanium contents of the biotite and hornblende of the massifs do not correlate with the corresponding values of the surrounding rocks (Fig. 3a–3d), and may thus, at least to some extent, be related to the pressure–temperature (PT) conditions of rock formation. The Fe content of biotite varies from the average of 50 mol% for the Märjamaa massif to 82–87 mol% for the Naissaare and



**Chemical composition of biotite, %**  
The separated biotite samples correspond to the whole rock samples in Table 1 in Soesoo & Niin, 1992

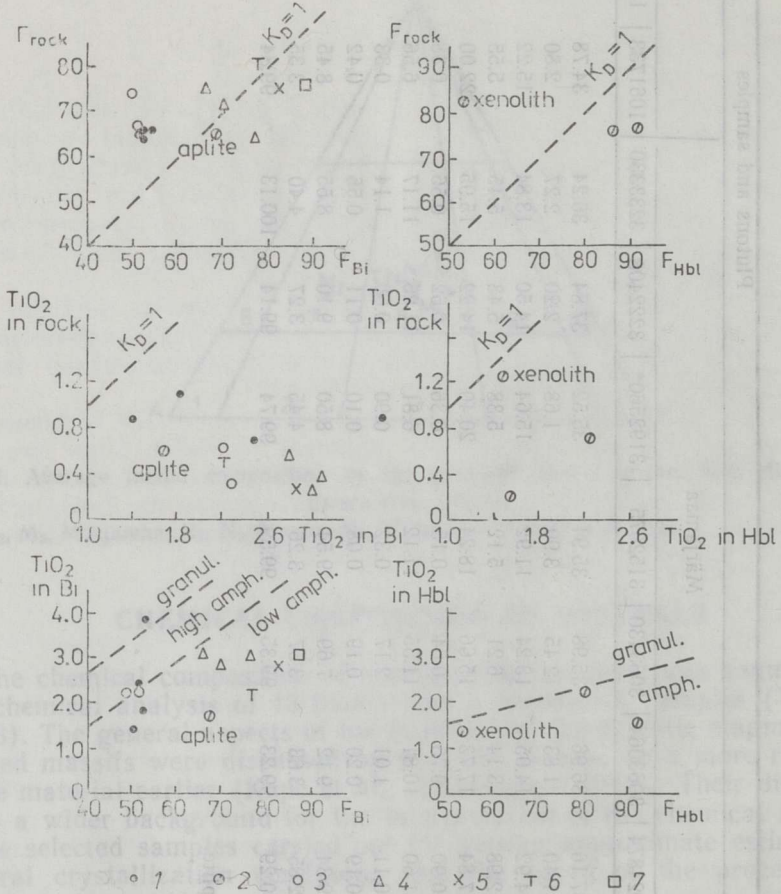
Component	Plutons and samples												
	Märjamaa						Neeme			Naisaare	Taebla	Ereda	
										2962725	3492942	3192768	
	3024874	3063064	3063430	3152675	3192560*	3222408	3233330	1061733	1151509	5033655			
SiO <sub>2</sub>	37.16	36.96	35.98	35.94	35.52	37.84	36.24	34.78	35.16	34.78	32.94	33.42	33.48
TiO <sub>2</sub>	1.40	1.83	2.45	3.90	1.68	2.20	2.27	2.80	3.07	3.00	2.85	2.18	3.05
Al <sub>2</sub> O <sub>3</sub>	14.92	14.05	13.24	11.92	15.64	14.50	13.84	15.22	14.36	14.86	13.67	16.34	16.47
Fe <sub>2</sub> O <sub>3</sub>	2.98	3.14	6.21	5.12	5.38	5.43	5.45	5.55	6.45	6.75	10.34	8.44	4.40
FeO	17.84	17.73	15.66	18.24	20.40	14.22	15.95	22.00	20.00	21.48	22.56	20.82	26.81
MnO	0.90	0.75	0.64	0.15	0.36	0.62	0.56	0.38	0.41	0.51	0.28	0.58	0.21
MgO	11.60	10.81	11.55	11.12	6.81	11.25	11.17	6.56	7.58	4.77	3.88	4.84	2.60
CaO	0.11	1.01	2.17	0.32	0.90	0.60	1.14	0.33	0.64	1.31	1.26	0.30	0.39
Na <sub>2</sub> O	0.19	0.20	0.19	0.08	0.10	0.11	0.56	0.42	0.15	0.14	0.20	0.04	0.19
K <sub>2</sub> O	9.34	9.12	7.69	9.54	8.50	9.10	8.55	8.45	7.74	8.28	6.00	9.28	7.79
l. o. i.	2.85	3.63	3.57	3.26	4.45	3.27	4.40	3.35	4.01	3.91	5.23	3.43	4.35
Total	100.29	99.23	99.35	99.59	99.74	99.14	100.13	99.84	99.57	99.79	99.19	99.67	99.74

\* biotite from aplite.

Table 3

Chemical composition of separated amphiboles of Märjamaa granites

Component	Sample		
	3043035	3052972	3242760
SiO <sub>2</sub>	38.26	42.06	38.56
TiO <sub>2</sub>	1.57	1.48	2.23
Al <sub>2</sub> O <sub>3</sub>	10.66	10.95	10.74
Fe <sub>2</sub> O <sub>3</sub>	6.05	4.71	6.19
FeO	26.15	14.73	22.27
MnO	0.65	0.30	0.52
MgO	1.48	9.61	3.83
CaO	9.20	10.72	8.82
Na <sub>2</sub> O	1.19	0.95	1.43
K <sub>2</sub> O	1.84	1.58	2.35
l. o. i.	2.51	2.34	2.58
Total	99.56	99.43	99.52

Fig. 3. TiO<sub>2</sub> and ferrous (F) content in rock and minerals.

Granulite-amphibolite fields for biotite after Drugova and Glebovitsky (Другова & Глебовицкий, 1965), for hornblende after Berezkin (Березкин, 1977). Analysis of rock and minerals of massifs: 1—3, Märjamaa (I, II, and III phase, respectively); 4, Neeme; 5, Naissaare; 6, Taebila, 7, Ereda.



Ereda massifs. It is noteworthy that the Fe/Mg ratio of the biotites of Märjamaa granite is quite stable in spite of the relatively wide variation range from 64 to 74% of the Fe content of the rock. A significantly higher Fe/Mg ratio was recorded only for biotite separated from aplite (sample 3192560). The highest Mg content for amphiboles was recorded for sample 3052972, separated from a melanocratic xenolith.

The data of the chemical analyses, displayed on the diagrams characterizing the biotite and amphibole metamorphism (Fig. 3e—3f), indicate that these minerals have formed under the conditions corresponding to low to moderate amphibolitic facies.

## ACCESSORY MINERALS

Among the rocks studied the granites of the Märjamaa massif are the richest in accessory and ore minerals. As most of the massifs contain more or less the same accessory minerals (e. g., titanite, zircon, apatite, and fluorite) and ore minerals (e. g. magnetite), their relative content has proven to be useful in the comparison of the composition of different massifs and different phases of each particular massif (Tables 1 and 4). In general, the Märjamaa granites are characterized by a relatively high content of accessory and ore minerals reaching 1—3% (Table 1). The composition of phase II is close to that of phase I, differing in the content of zircon and fluorite. The first phases of the Neeme and Naissaare massifs are similar in general mineral composition, having only slightly different distribution of accessories. In both massifs the most common accessory minerals are zircon and apatite (Table 4), while the contents of titanite and fluorite differ to some extent. A relatively stable content of ore minerals, including magnetite and ilmenite, is also characteristic of all these rocks.

In contrast, in the granites of the Taebila massif and phase III of the Märjamaa massif the main accessory mineral is fluorite, and the content of other minerals is always modest. By way of exception, the Taebila granites contain garnet.

Most of the accessory minerals are of irregular shape. Pyrite, titanite, and apatite occur in a form of undeveloped crystals: pyrite as cubic or octahedral aggregates, titanite as yellow or brownish-yellow octahedrons, and apatite as colourless or slightly greenish prismatic crystals. As an exception, zircon is represented by a number of varieties, from the idiomorphic prismatic crystals to rounded and corroded grains, allowing of correlations of massifs as well as of their phases.

Among the granites of phase I of the Märjamaa massif (drill core F 306, see Fig. 1a), clear idiomorphic and, to some extent, panidiomorphic prismatic crystals are prevailing. Zonality can be observed rarely and most of the zircon grains contain many needle-like or irregular inclusions. The usual ratio of length to width (elongation ratio) of crystals is 2:1, but some crystals can have the elongation ratio up to 6:1. In the granite of phase II (cores F 304, F 314), most of the zircon crystals show clear zonality and are fractured and rich in inclusions, and they are mostly transparent and idiomorphic.

In the core F 305, which was drilled at the supposed contact zone between phases I and II of the granite, three varieties of zircon, most likely representing different generations, can be distinguished. One variety is represented by more or less rounded dark grains, mostly forming the core of another variety. This variety, represented by translucent or opaque (metamict) zircon, sometimes with developed zonality, in turn often forms the core of a third zircon variety. The transparent, clearly idiomorphic

grains of the last zircon variety occur also separately, often with well-developed zonality.

The zircon from Märjamaa aplite-granite has also quite characteristic features (core F 319, see Pl. I, figs. 5—7). The grains are mostly idiomorphic, but are not particularly clean and transparent. Zonality, fracturing, and inclusions can be observed. Twinned crystals similar to those formed by an intergrowth of two idiomorphic crystals occur (Pl. I, fig. 7). In addition to the idiomorphic crystals, panidiomorphic crystals with a new overgrowth layer visible in some of the crystals are present.

Table 4

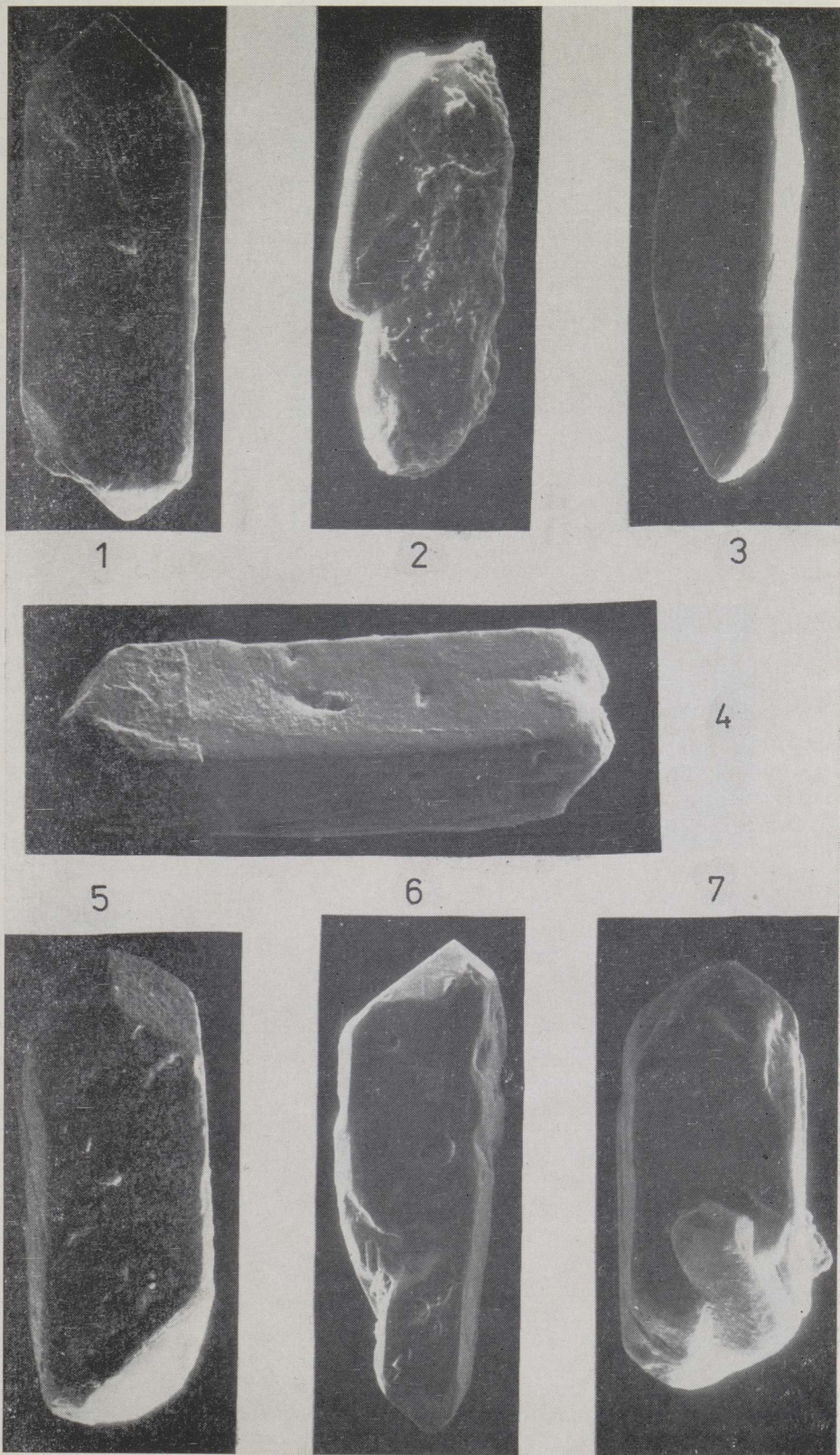
Percentage of opaques and accessories in granites

The content of minerals in a sample was summed to 100%

Pluton, sample	Pyr + Pyrr	Ilm + Mt	Sph (Ti)	Zr	Ort	Ap	Fl	Others	
Märjamaa									
3063064	0.5	31.4	34.6	2.6	0.3	28.0	2.8		
3063430	1.3	33.0	31.2	4.4	0.3	28.0	1.8		
3052780	—	37.8	4.5	31.1	2.2	24.4	—		
3052972	—	52.3	9.1	27.3	3.4	7.9	—		
3032833	2.6	31.1	10.4	14.3	—	39.0	2.6		
3033338	—	41.1	19.6	12.7	—	25.4	1.2		
3042288	—	25.0	11.1	47.2	2.8	5.6	8.3		
3042790	—	25.7	4.4	18.1	1.1	1.1	49.7		
3043035	—	34.4	9.8	29.5	3.3	—	23.0		
3142676*	3.1	62.5	1.6	28.1	—	1.6	3.1	Turm	1.8
3192560**	7.3	7.3	1.8	7.3	—	36.3	—	Leuk	38.2
3222408	4.7	53.1	0.5	2.6	—	8.3	30.8		
3233330	4.6	56.7	1.1	3.7	2.3	7.6	23.6	Leuk	0.4
Neeme									
1061733	—	3.0	54.6	10.2	0.8	28.2	3.2		
1151509	—	42.3	8.7	27.9	—	13.8	7.3		
Naissaare									
2962725	—	17.8	4.4	13.4	1.0	23.3	40.1		
2962820	—	26.1	3.2	19.3	2.3	11.5	34.4	Ep	3.2
Taebila									
3483550	—	8.7	0.9	3.5	—	0.9	78.2	Ep	5.2
								Gr	1.7
								Leuk	0.9
3492942	1.2	18.3	8.3	4.1	0.6	2.4	61.5	Ep	1.8
								Gr	1.8

\* K-granite in contact with surrounding rock; \*\* aplite; + a few grains; — not found.

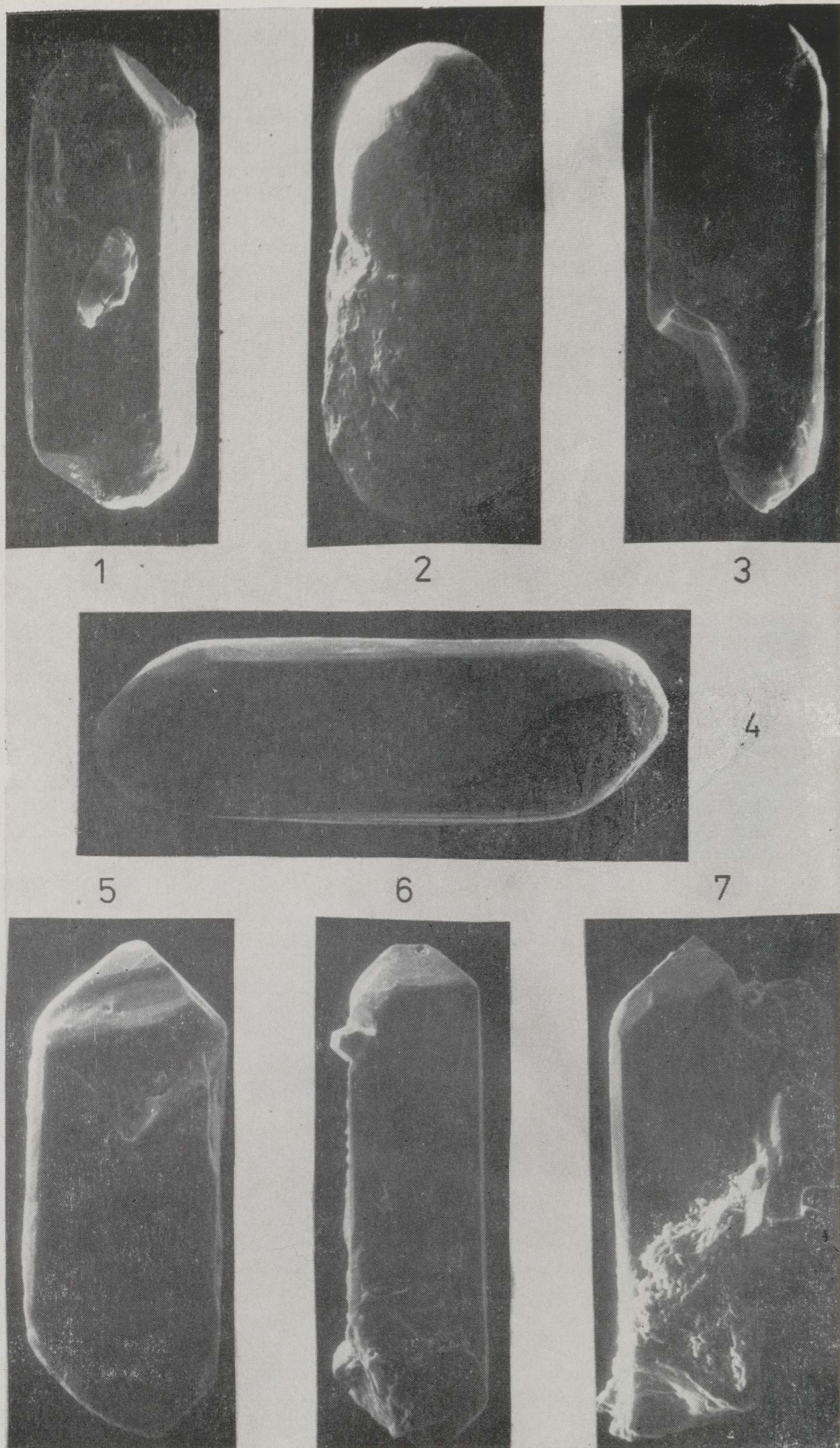




SEM microphotographs of zircon crystals from Mārjamaa porphyreous K-granite massif,  $\times 1000$ .

Figs. 1—4, drill core F 323; figs. 5—7, drill core F 319. Photo Ursula Moldov.





SEM microphotographs of zircon crystals from Taebla porphyreous K-granite massif,  $\times 1000$ .

Figs. 1—4, drill core F 349; figs. 5—7, drill core F 348. Photo Ursula Moldov.



In the leucocratic phase III of the Märjamaa granite (F 322, F 323), mostly clean idiomorphic zircon crystals occur (Pl. I, figs. 1—4). These crystals contain a few inclusions, but lack fracturing and zonality. The panidiomorphic grains occurring mostly as separate crystals, sometimes also as cores of another variety, are darker, less clean, and often fractured. Many zircon grains bear traces of corrosion.

Zircon grains in the small Taebla massif (F 348, F 349, see Pl. II) resemble in general terms the above-described varieties, showing even a greater extent of variation. Zonality and fracturing can be observed both in idiomorphic and panidiomorphic crystals. Often, idiomorphic zircon crystals envelope a darker and more metamict panidiomorphic crystal, which can contain in turn an opaque core. Also grains with traces of corrosion and epitaxial crystals can be observed (Pl. II, fig. 7). However, most of the zircon grains originating near the contact zone of the massif (Fig. 1d, core F 348) show quite distinct features. In these grains, inclusions are not present or not visible, the grain shape varies from regular to irregular, and sometimes aggregates of grains occur.

The zircon grains from the Neeme (Fig. 1b, F 106 and F 115) and Naissaare (Fig. 1c, F 296) massifs are very similar to each other. Idiomorphic and quite regular-shaped crystals, with the elongation coefficient from 2 to 4, are prevailing. Zircon grains are relatively big and zonality is common, while corrosion of the grains is uncommon. The described zircon grains resemble those of phases I and II of the Märjamaa massif.

## DISCUSSION

Investigations of small plutons of porphyreous granites in recent years have shown them to consist of two or more magmatic phases of rocks, analogical to typical rapakivi massifs. Earlier petrochemical and partially mineralogical findings (Soesoo & Niin, 1992) reveal substantial similarities between potassium granites of small plutons and large rapakivi massifs (Wiborg, Salmi, Korosten). At the same time it is possible that the first, most melanocratic phase of rocks seen in big rapakivi massifs may be absent in small plutons.

Typical for big massifs is the existence of numerous xenoliths of country rocks in their peripheral part. This phenomenon has been described in detail with reference to the Wiborg massif (Simonen, 1987, p. 9) and his satellite Suomenniemi batholite (Rämö, 1991). The rocks of phase II of the Märjamaa pluton, the biggest pluton in North Estonia, differ from other plutons first of all in regard to their heterogeneity — they may be influenced in places by xenoliths of surrounding rocks. At the same time the relative homogeneity of small potassium granite massifs refers to the probability that assimilated xenoliths play clearly a less important role here than in bigger massifs.

It is supposed that the crystallization temperature of the Wiborg rapakivi pluton was more than 800°C (Vorma, 1972). According to Velikoslavinsky and coworkers (Великославинский et al., 1978), the crystallization temperature interval for the granitoid phases of rapakivi is 800—500°C. Our earlier estimation (using Buddington's and Barth's geothermometers) gives the crystallization temperature for the Märjamaa massif as 650—550°C.

The Al content of amphiboles serves as the basis for estimating another parameter of crystallization—pressure (Hammarstrom & Zen, 1986; Hollister et al., 1987). According to the composition of the amphiboles of the Märjamaa pluton (Table 3) the pressure was in the interval of 5.2—6.5 kbar. It is interesting to note that the same level of pressure ( $P=5-6$



kbar) has been estimated for the metamorphic rocks of the West-Estonian block surrounding the Märjamaa pluton (Pyyppä et al., 1983). Such proposed PT conditions of crystallization of the Märjamaa pluton correspond to the conditions of amphibolitic facies. The chemical composition of biotites and amphiboles (Fig. 3e—3f) refers to the same conditions.

New zircon age determinations using the U—Pb method gave the result 1.626 Ga (Kirs et al., 1991). The isotopic age of biotites from all Estonian potassium granite plutons determined by the K—Ar method is 1.65—1.62 Ga (Pyyppä, 1974). If the estimation of the crystallization temperature of Märjamaa granite (max. 650°C) is valid, it follows that the cooling of the pluton down to the temperature of biotite blocking (300°C) occurred very quickly: during an interval not revealed by usual determination methods.

Attempts have been made to restore the cooling process in small zonal granodioritic plutons on the ground of the K—Ar ratio in the minerals of Spider Lake Granite and Chain of Ponds plutons, located on the Canadian Shield west from Quebec (Heizler et al., 1988). On the ground of changes in the composition of Hbl, Bi, Ksp (Or and Mi) in the interval of 550—150°C, the whole estimated cooling process continued for 60 million years, but the temperature drop from 550 to 350°C (until the blockage of biotite) lasted only 4 million years. Similarly, the small plutons of North Estonia are supposed to have been able to keep a rather steep cooling curve till 300—350°C with less rapid cooling afterwards. At the time of cooling to 350°C, a fresh potash feldspar appeared in the surrounding gneiss (Taebpla pluton, drill core F 348). This explains also, at least partially, the relative heterogeneity of the massifs, the xenoliths in these, and sharp contacts between granites and surrounding rocks.

The distribution of accessories and the peculiarities of zircon generations in a possible xenolith (drill core F 305), in aplite (F 319), and in near-contact granites (F 314, F 348) are also proofs of a considerable heterogeneity and multistage formation process of small potassium granite plutons. Using the morphological criteria worked out for the granites of the Ukrainian Shield (Робул, 1989), the following genesis of the zircons in the North Estonian potassium granites can be proposed:

- (1) zircons from phases I and II of the Märjamaa massif are evidently early magmatic;
- (2) zircons from the Taebpla massif and from phase III of the Märjamaa massif are late magmatic with subhedral cores of early magmatic origin;
- (3) intergrown crystals of zircon in granite-aplite (F 319) and partially in leucocratic granites of Taebpla are very similar to the zircons of the pneumatolytic stage from the Korosten rapakivi pluton.

All the material presented here strengthens the conviction that the North Estonian plutons have had, regardless of their modest size, a clearly multistage evolution, similar to that of big rapakivi plutons.

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## POHJA-EESTI ALUSKORRA VÄIKESTE PORFÜÜRILAADSETE KAALIUMGRANIITIDE MINERALOOGIAST

Vello KLEIN, Mare KONSA, Mati NIIN

Uuritud kivimite mineraalse koostise ning mineraalide keemilise koostise määrangud võimaldavad anda mõningaid hinnanguid mineraalide kristallisatsioonitingimuste kohta ning selgitada ka protsesside arengu võimalikku kiirust. Tsirkooni tüpomorfised erimid on abiks massiivide varaja hilismagmaliste faaside eristamisel.

## О МИНЕРАЛОГИИ МАЛЫХ ПОРФИРОВИДНЫХ КАЛИЕВЫХ ГРАНИТОВ КРИСТАЛЛИЧЕСКОГО ФУНДАМЕНТА СЕВЕРНОЙ ЭСТОНИИ

Велло КЛЕЙН, Маре КОНСА, Мати НИЙН

Изучен минеральный состав породы и определен химический состав минералов, что позволило оценить условия кристаллизации минералов, а также возможную скорость развития этих процессов. Типоморфные разновидности циркона могут быть полезны при выделении в массивах ранне- и позднемагматических фаз.