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Anorogenic magmatic rocks in the Estonian crystalline basement

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Abstract. The anorogenic magmatic rock bodies of the Estonian crystalline basement belong to the Fennoscandian Palaeo–Mesoproterozoic Rapakivi Province and include the huge composite Riga batholith (250 km × 230 km in subsurface area, mostly in NW Latvia), as well as at least five granite stocks (Naissaare, Märjamaa and its Kloostri satellite, Taebla, Neeme, and Ereda) and the quartz monzodioritic Abja stock in the Estonian mainland. The Riga batholith contains both mafic and silicic rocks, as several Fennoscandian rapakivi complexes do. The granite stocks appear on geophysical maps as gravity and magnetic minima, and they consist of pink, medium- to coarse-grained, microcline-megacrystic, partly trachytoid biotite (in Märjamaa and Naissaare also with hornblende) granite, locally cut by aplitic and microsyenitic dykes. As an exception, the Märjamaa stock is more differentiated and has an anomalously high magnetic central part composed of hybrid granodiorite with hornblende as the main mafic mineral. The Abja quartz monzodiorite stock is strongly magnetic and consists of a dark grey, massive, medium-grained, partly weakly gneissose rock with abundant accessory apatite and titanomagnetite, and is intersected by veins of fine- to medium-grained, slightly porphyritic plagioclase-microcline granite. The major, REE and other trace element contents of the granitic rocks are close to or overlap those of the typical Finnish rapakivis and are best comparable with the less differentiated granitic phases. The Märjamaa granodiorite and the Abja quartz monzodiorite are enriched in Sr, Ti, and P. In Nd and Pb isotopic composition, the felsic and mafic rocks resemble corresponding rocks of the Finnish rapakivi complexes, indicating an approximately chondritic source for Nd in the mafic rocks of the Riga batholith and the Abja intrusion, and a Palaeoproterozoic (Svecofennian) source for the felsic rocks. The T_{DM} model ages of the felsic rocks range from 1890 to 2100 Ma.

Key words: Proterozoic, Estonian basement, anorogenic magmatism, rapakivi, geochemistry, age.

INTRODUCTION

Anorogenic (independent of the Svecofennian orogenic framework) magmatic rocks in the Estonian territory were discovered in the early 1960s by geophysical mapping and deep drilling through the 150–800 m thick Neoproterozoic (Vendian) and Palaeozoic sedimentary blanket (Tikhomirov 1965; Bogatikov & Birkis 1973; Kuuspalu 1975; Velikoslavinsky et al. 1978; Puura et al. 1983, 1992a, 1992b; Soesoo & Niin 1992; Kirs & Petersell 1994; Rämö et al. 1996; Niin 1997, 2002; All et al. 2004).

The anorogenic rock bodies in the Estonian crystalline basement include the huge composite Riga batholith (250 km   230 km in subsurface area under the Gulf of Riga and Kurzeme Peninsula in NW Latvia), as well as at least five minor granitoid stocks (Naissaare, Märjamaa and its Kloostri satellite, Taebla, Neeme, and Ereda) in northern Estonia and the quartz monzodioritic Abja stock in south-western Estonia (Fig. 1). Structurally, the anorogenic rock bodies belong to the Fennoscandian Palaeo–Mesoproterozoic Rapakivi Province (Rämö & Haapala 1995; Koistinen 1996; Puura & Floden 1999).

The purpose of the present article is to give a geological-petrographical overview of the plutons and report new geochemical data about the rocks.

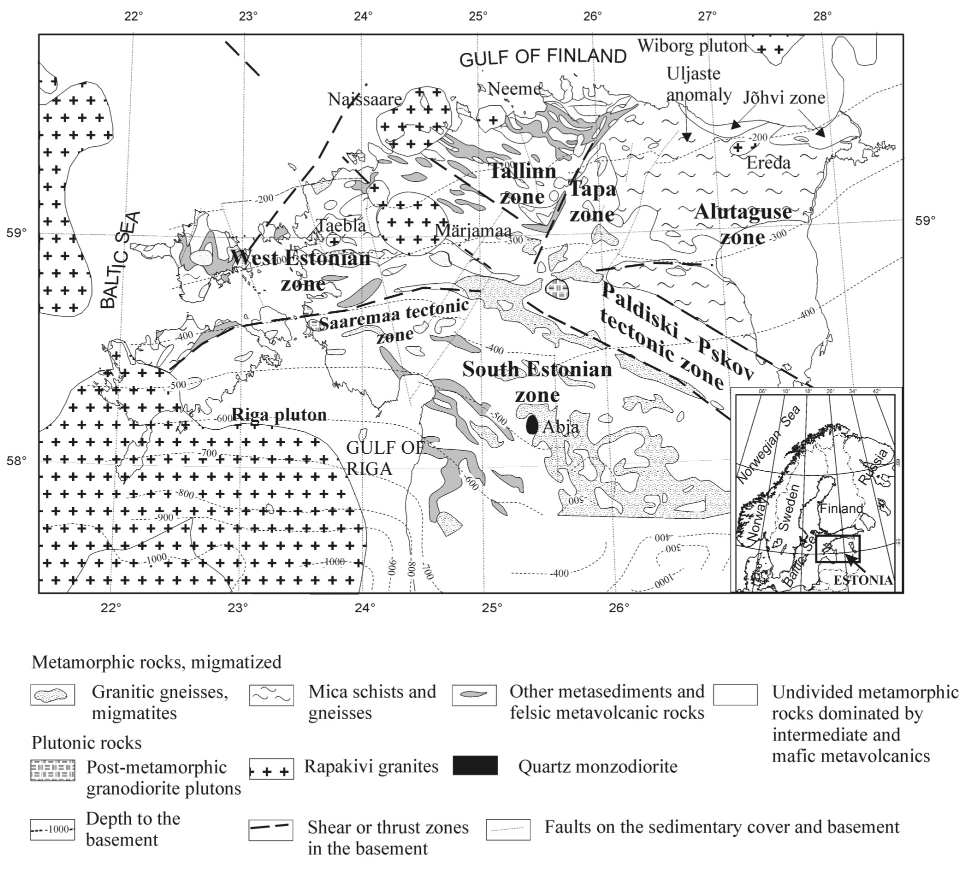

Fig. 1. Geological sketch map showing the distribution of anorogenic plutons of the Estonian crystalline basement. Modified from the bedrock map published by Koistinen (1996).

THE STRUCTURE AND ROCK ASSOCIATIONS OF ANOROGENIC PLUTONS

The composite Riga batholith

The Riga batholith forms the southern part of the Riga–Åland–Bothnia rapakivi subprovince (Puura & Floden 1999; Rämö & Korja 2000; Haapala et al. 2004) and contains both mafic and silicic rocks, petrographically and geochemically analogous to the typical members of the Fennoscandian rapakivi-anorthositic suite (Rämö et al. 1996). As in the case of other large rapakivi granite batholiths, considerable effect of crustal thinning – on a 10 km scale – has occurred in this area (Korja et al. 2001; Puura & Floden 1999, 2000). Zircons from the leucogabbronorite and the biotite-hornblende granite of the Riga pluton have U-Pb ages of 1576 ± 2 and 1584 ± 7 Ma, respectively (Rämö et al. 1996).

Granosyenitic, syenitic, and quartz monzonitic rocks (mangeritic rocks after Bogatikov & Birkis, 1973) and associated gabbro-anorthosites and ultramafic rocks are found in the southern part of the batholith (Fig. 1). Typical shallow-crustal granites with rapakivi texture are found in the central part (Bogatikov & Birkis 1973), while subvolcanic granophyres occupy large areas in its northern part – on the basement of Ruhnu Island in the Gulf of Riga and in the south-western part of Saaremaa Island (Kuuspalu 1975; Puura et al. 1983). Adjacent to the northern flank of the main granitoid body, a pile of subhorizontally layered rapakivi-related volcanic rocks is found. These are phenocrystic rhyolites (or quartz porphyries) recovered from a drill core on the Undva Peninsula, western Saaremaa, underlain by plagioclase porphyrites (Niin 1976).

Bogatikov & Birkis (1973) subdivided the mafic rocks distributed in the southern part of the Riga batholith into two groups: one consists almost exclusively of anorthosites, while the other features a more complex association of rocks, including anorthosite, gabbro-anorthosite, gabbronorite, troctolite, and melatroctolite. The contacts between various rock types are transitional. Typically the rocks are dark grey, mostly coarse- to very coarse-grained and occasionally display oriented fabric. Plagioclase (mostly $An_{50–55}$) forms subhedral to euhedral, homogeneous, in places weakly zoned grains often containing inclusions of titanomagnetite. The plagioclase crystals of anorthosite display dark blue iridescence. Alkali feldspar occurs as interstitial grains or antiperthitic inclusions in plagioclase. Its amount increases abruptly close to the contacts of the anorthosites with silicic rocks, where perthitic alkali feldspar partly replaces plagioclase. Composite kelyphitic coronas have commonly intensively developed around olivine and orthopyroxene grains. Ca-poor pyroxene is inverted pigeonite. Weakly serpentinized olivine ($Fa_{35–44}$) is more idiomorphic in gabbros than in anorthosites. Apatite, zircon, and rutile are typical accessory minerals. According to Bogatikov & Birkis (1973), the melatroctolites (called plagioclase-bearing peridotites by these authors) are black, massive rocks, containing up to 70 vol% olivine (Fa_{38}), 20–27 vol%

plagioclase (An_{50-54}), a few per cent clinopyroxene and orthopyroxene (Fs_{30}), and 5–6 vol% ilmenite. Composite kelyphitic coronas are common.

The dark grey porphyritic basalt (plagioclase porphyrite) underlying the quartz-feldspar porphyry in the Undva drill core in the northern part of the batholith contains 3–10 vol% light-coloured euhedral plagioclase phenocrysts (An_{40-50}) that are usually 2–3 mm, rarely up to 4–5 cm, in length. Alkali feldspar and quartz occur in minor amounts. Interstitial augite and pigeonite have in part been altered to amphibole and mica.

The quartz monzonitic rocks in the southern part of the Riga batholith are brownish, mostly coarse-grained porphyritic rocks containing megacrysts of euhedral, mesoperthitic alkali feldspar. Plagioclase is often replaced by alkali feldspar and varies in composition from andesine to oligoclase. The patch- and vein-type perthitic inclusions in microclinic feldspar have the same composition. Mafic minerals (biotite and hastingsitic hornblende with rare clinopyroxene inclusions) account for up to 10 vol% of the rock. Quartz is ubiquitous. Accessory minerals are magnetite, zircon, monazite, fluorite, anatase, tourmaline, and garnet.

The granitic rocks forming the central part of the Riga massif are mostly pink, massive, coarse-grained biotite-hornblende rapakivi granites, petrographically identical to the wiborgite and pyterlite of the Wiborg batholith (see Rämö & Haapala 1995). Typical accessory minerals are apatite, zircon, ilmenite, magnetite, and fluorite. Even-grained and aplitic granites occur in minor amounts.

The subvolcanic biotite granite porphyries in the northern part of the Riga batholith on Saaremaa and Ruhnu islands resemble the granophyres (graphic granites) of the Gulf of Bothnia (Eskola 1928). They contain euhedral, 2–5 mm, rarely up to 10–20 mm long phenocrysts of albite and microperthitic orthoclase. Both the rapakivi (i.e. alkali feldspar mantled with plagioclase) and antirapakivi (i.e. plagioclase mantled with alkali feldspar) textures are found. Quartz occurs as euhedral grains, which, however, began to crystallize later than the intratelluric feldspar megacrysts. The groundmass is granophyric, partly spherulitic, and contains miarolitic cavities.

The presence of several intrusive phases in the Riga rapakivi batholith is obvious, but has been documented in detail utilizing combined drill core and geophysical data only for the southern part of the batholith where mafic and ultramafic rocks prevail (Bogatikov & Birkis 1973). Except the local gravity and magnetic highs caused by the gabbro-anorthosite suites in that part of the batholith, most of this large pluton is characterized by an extensive gravity low (Fotiadi 1958; Kinck et al. 1993) and variable, nonlinear, positive and negative magnetic anomaly patterns (Korhonen et al. 1995). These anomalies fit the low-density and weak magnetization of the rapakivi suites measured in the drill core samples. Urban & Tsybulya (1988) interpreted the overall low-gravity field, the variable magnetic anomalies, and high thermal fields, measured for the northern part of the Riga batholith, as resulting from a ca. 5 km thick granitic sheet underlain by a ca. 20 km thick body of interbedded mafic and granitic rocks.

Porphyritic granite stocks in Estonia

In northern and northwestern Estonia there are five stocks of porphyritic potassium granite, penetrated by 61 drill holes (Kuuspalu 1975; Soesoo & Niin 1992; Koistinen 1996). The intrusions were in past supposed to be somewhat older than the rapakivi granites proper (Kuuspalu 1975; Soesoo & Niin 1992; Koistinen 1996), but are nowadays correlated in age to the Wiborg rapakivi batholith and its satellites (Rämö et al. 1996). The potassium granites from the stocks typically comprise pink, medium- to coarse-grained, microcline-megacrystic, massive, partly trachytoid syeno- and monzogranitic rocks, which are locally cut by aplitic and microsyenitic dykes (Kuuspalu 1975; Kirs 1986; Soesoo & Niin 1992). The characteristic mafic mineral in granites is annitic to siderophyllitic biotite.

In places the potassium granites from the Naissaare, Neeme, and Märjamaa plutons contain also hornblende, whose character, together with their lower SiO_2 content (65–68 wt%), implies that they may represent an early (the first?) intrusive phase of magmatism (Soesoo & Niin 1992; Soesoo 1993). The Märjamaa stock has a highly magnetic granodioritic or quartz monzonitic central part, in which hastingsitic hornblende is the main mafic mineral and SiO_2 varies from 62 to 68 wt%. This central zone contains ≤ 20 cm long dark grey, fine-grained, lens-like, disaggregated enclaves, and has been interpreted to be of hybrid origin.

Euhedral phenocrysts of variably ordered, vein-perthitic microcline contain 20–35 wt% exsolved albite component (Kirs & Utsal 1981). Plagioclase-mantled alkali feldspar ovoids (the rapakivi texture) are lacking; this texture is found only in the granites of the Riga batholith.

The composition of the plagioclase is usually $An_{30–35}$, but increases to An_{40} in the hybrid parts of the Märjamaa granodiorite (Kirs 1986). Typical accessory minerals include apatite, zircon, fluorite, magnetite, titanite, and allanite. Molybdenite and galena are met locally. A small but interesting difference to the Finnish rapakivi granites is in Ti minerals: in the Finnish rapakivi granites the typical accessory Ti minerals are ilmenite and anatase, titanite is known only from the Obbnäs granite in the southern coast of Finland (Kosunen 1999).

The porphyritic K-granite stocks (Ereda, Neeme, Naissaare, Taebla, Kloostri) appear on geophysical maps as small gravity and magnetic minima. Due to the low susceptibility of the granitoid rocks, the internal structure of the intrusive bodies cannot generally be traced from the magnetic anomaly maps, although internal contacts are fixed in several cases by petrological studies of core samples.

The strongly magnetic core part of the Märjamaa stock is surrounded by a magnetic minimum that is a porphyritic hornblende-bearing biotite granite and is interpreted to represent the main intrusive phase of the stock. The little Kloostri satellite off the northwestern part of the stock also shows a magnetic minimum and has been interpreted as the third intrusive phase of the pluton (Soesoo & Niin 1992; Soesoo 1993).

The mafic Abja stock

The mafic Abja stock in southern Estonia (Fig. 1) is strongly magnetic and consists of dark grey, medium-grained, in part weakly gneissose quartz monzodiorite. The main minerals are plagioclase ($An_{35–40}$), hornblende, biotite, cryptoperthitic orthoclase, and quartz (Puura et al. 1983; Kirs & Petersell 1994). A characteristic feature is the occurrence of accessory apatite and titanomagnetite. Quartz monzodiorite is intersected by veins of fine- to medium-grained plagioclase-microcline granite. It is in places slightly porphyritic with euhedral alkali feldspar megacrysts. Apatite, zircon, monazite, allanite, and magnetite are typical accessory minerals.

GEOCHEMICAL FEATURES OF ANOROGENIC MAGMATIC ROCKS

Representative geochemical data are presented for Estonian silicic and mafic rocks in Table 1 and Appendix. Rock samples from drill cores were analysed in X-ray Assay Laboratories Ltd in Canada using X-ray fluorescence spectrometry (XRF), inductively coupled plasma spectrometry (ICP), direct current plasma spectrometry (DCP), inductively coupled plasma mass spectrometry (ICP-MS), neutron activation analysis (NA), atomic absorption spectrometry (AA), and graphite furnace atomic absorption spectrometry (GFAA) methods. The F content was determined by an ion selective method at the geochemical laboratory of the Department of Geology, University of Helsinki.

Silicic rocks

Geochemically, the rapakivi granites from stocks and from the Riga batholith are subalkaline (Fig. 2), metaluminous or slightly peraluminous ($Al_2O_3/CaO + K_2O + Na_2O$ mol. proportions less than 1.1). They show high FeO*/MgO ratios (4.5–7) and normal or high F contents (0.05–0.4 wt%) (Bogatikov & Birkis 1973; Petersell & Kirs 1992). In general, the major-element composition of the granites from the Estonian stocks overlaps that of typical Finnish rapakivi granites. However, the former contain somewhat less Al and Fe (Kuuspalu 1975; Kirs et al. 1991; Soesoo & Niin 1992).

In the ternary Rb-Ba-Sr diagram the rocks are comparable to the less differentiated granitoid phases from the Wiborg and Laitila batholiths (Fig. 3) and the Obbnäs granite of southern Finland (Kosunen 1999). The granodiorite of the Märjamaa stock and the biotite granite of the Neeme stock are richer in Sr, Ti, and P (Petersell & Kirs 1992). The biotite granites of the Ereda stock and the aplitic granite veins from the Neeme stock are more differentiated (Petersell &

Table 1. Whole-rock geochemical analyses of the anorogenic granitic and associated mafic rocks of Estonia. Oxides in wt%, elements in ppm

	Sample										
	25	87	44	5808*	5807*	60	H53	302	327	106	92[(1]
SiO_2	51.20	48.10	43.10	54.17	71.41	69.00	73.30	64.50	73.70	71.10	51.23
TiO_2	0.26	2.49	3.40	1.50	0.37	0.59	–	0.82	0.21	0.44	2.13
Al_2O_3	25.90	18.10	13.60	14.03	11.99	14.80	12.90	15.00	12.20	13.20	13.87
Fe_2O_3	1.80	10.30	18.20	11.30	4.97	3.10	2.84	4.91	2.82	3.46	11.77
FeO	1.00	6.70	13.50	8.60	0.10	1.70	2.00	2.50	1.60	2.20	5.77
MnO	0.04	0.12	0.24	0.15	0.03	0.04	0.06	0.11	0.04	0.05	0.17
MgO	0.49	3.24	6.58	3.87	0.46	0.42	0.24	1.14	0.45	0.93	3.58
CaO	12.60	9.25	8.72	6.13	0.23	0.84	0.99	2.61	0.75	1.51	6.82
Na_2O	4.26	3.67	2.85	2.58	2.46	4.22	3.58	3.01	2.28	2.64	2.96
K_2O	0.96	1.28	0.68	2.31	6.29	5.60	5.54	6.17	5.96	5.00	2.76
P_2O_5	0.11	1.42	2.14	0.43	0.05	0.14	0.05	0.35	0.04	0.12	1.71
$H2_2O^+$	0.50	0.40	0.50	1.50	0.60	0.70	0.40	0.40	0.50	0.60	0.60
LOI	2.39	0.08	0.46	1.35	0.65	1.00	0.05	0.31	0.62	0.70	0.48
Total	101.51	105.15	113.97	107.92	99.61	102.15	101.95	101.83	101.17	101.95	103.85
S	25	669	2770	940	95	104	25	318	25	25	3280
F	53	1100	1400	409	63	88	2000	2800	300	1300	2583
Cl	108	120	184	101	210	370	357	225	150	159	784
Br	0.5	0.5	2	2	5	2	1	1	0.5	0.5	3
B	31	17	16	5	5	28	32	29	21	19	13
As	0.8	1.8	1.6	1	0.6	3.1	5.8	0.7	0.3	0.8	2.3
Se	0.1	0.1	0.1	1	0.5	0.1	0.1	0.1	0.1	0.1	0.4
Sb	0.05	0.05	0.05	0	1.7	0.1	0.2	0.1	0.05	0.05	0.1
Au	–	–	–	1	1	–	–	–	–	–	1.0
Ag	–	–	–	1	0.5	0.6	–	0.9	–	0.2	0.5
Hg	14	20	27	3	3	17	14	14	20	20	9
Cr	10	35	0	44	19	19	41	26	22	28	45
Ni	15	27	101	47	7.25	5	6	10	5	6	19
Co	3	51	90	30	2	4	1	11	–	5	31
Sc	7	20	27	22	5	8	4	12	7	4	18
V	33	171	321	170	22	10	8	46	4	26	174
Cu	9	25	46	71	23.75	1	7	5	2	1	29
Pb	1	18	1	18	22.5	1	44	28	17	11	41
Zn	11	71	163	116	66.95	34	72	132	63	56	147
Bi	1	1	1	3	3.5	1	2	1	1	1	2.3
Cd	0.1	0.1	0.1	0	0.2	0.1	0.1	0.1	0.1	0.1	0.2
In	0.1	0.1	0.1	3	3	0.1	0.1	0.1	0.1	0.1	2

Table 1. *Continued*

	Sample										
	25	87	44	5808*	5807*	60	H53	302	327	106	92[1]
Sn	2	8	1	3	9	2	6	1	7	10	11
W	12	15	13	1	1	18	39	17	25	20	9
Ge	–	–	–	5	5	–	–	–	–	–	5
Mo	0.5	0.5	0.5	1	2.5	0.5	2	3	0.5	0.5	0.7
Be	2	4	6	1	3	4	12	6	6	6	4
Ba	374	687	821	658	864	1660	1350	3040	2190	952	2457
Sr	677	421	294	179	32	108	81	542	184	220	1400
Rb	13	30	9	61	163	140	225	203	185	244	69
Cs	0.5	1	1	2	3.8	3	4	1	0.5	3	2
Tl	0.2	0.4	0.05	0	0.9	0.9	1.3	1.1	1	1.5	0
Ga	17.3	20.4	29.9	23	18	29.7	20.4	27	20.6	19.2	27
Li	26	10	16	18	13	41	41	39	33	50	16
Ta	0.5	0.5	0.5	0	1.1	1	3	2	2	3	1
Nb	4	7	12	10	22.5	27	28	37	30	33	22
Hf	0.7	4.1	3.1	–	–	17	9	16	9.5	7.6	10
Zr	33	163	91	248	424	656	295	573	355	294	359
Y	21	25	29	45	67	66	106	71	147	55	53
Th	0.5	3.4	0.7	6.1	20.5	15	25	16	43	33	12.2
U	0.1	1.3	1	1.7	7.45	3	14.4	3.7	1.9	4.5	3.0
La	6.1	31.4	51.6	34.3	39.5	69.6	77	133	297	96.1	192.7
Ce	11.7	67.1	111	88.2	101.1	136	143	282	528	183	387.7
Pr	1.3	7.8	12.7	9.7	8	15.1	15.1	33.8	59.2	18.6	47.0
Nd	5.5	36.4	58	37.9	34.2	60.4	58.8	153	239	67	176.0
Sm	1.4	7.5	10.9	8.6	8.4	10.4	10.1	22.3	31.4	10.6	25.8
Eu	1	2.5	3.3	2.2	1	2.4	2	4.3	3.4	1.3	6.0
Gd	1.3	6.6	10.3	8.4	7.9	7.5	9.7	16.2	21.6	7.4	18.9
Tb	0.2	1	1.5	1.4	1.5	1.2	1.6	2	3.1	1.1	2.0
Dy	1.1	5.7	8.9	8.1	9.5	7.3	10.7	13	16.8	6.2	11.2
Ho	0.25	1.14	1.76	1.71	2.17	1.9	2.4	2.43	3.21	1.25	2.0
Er	0.6	3.1	5	4.7	6.1	4.7	7.4	7	8.4	3.6	5.1
Tm	0.1	0.4	0.7	0.7	0.9	0.7	1.3	1	1.2	0.5	0.7
Yb	0.6	2.5	4.1	4.5	6.2	4.9	9.6	6.2	7	3.5	4.1
Lu	0.1	0.61	0.68	0.7	0.95	0.78	1.63	0.95	0.98	0.5	0.6

Analyses made in the X-ray Assay Laboratories. Canada. Methods: XRF (major components and S, Sn, Ba, Sr, Rb, Nb, Zr, Y); ICP (Br, Ag, Ni, Co, Sc, Cu, Pb, Zn, Mo, Ga, Li); DCP (B, V, Ge, Be); NA (As, Sb, Cr, W, Cs, Ta, Hf, Th, U); AA (Cd, In); GFAA (Se); ICP (Au, Bi, Tl); ICP-MS (REE); wet chemical (FeO, H_2O, Cl, Hg). F determined by an ion selective method at the geochemical laboratory, Department of Geology, University of Helsinki. For sample codes see Appendix. * average of 2 analyses; [1] average of 3 analyses; – not determined.

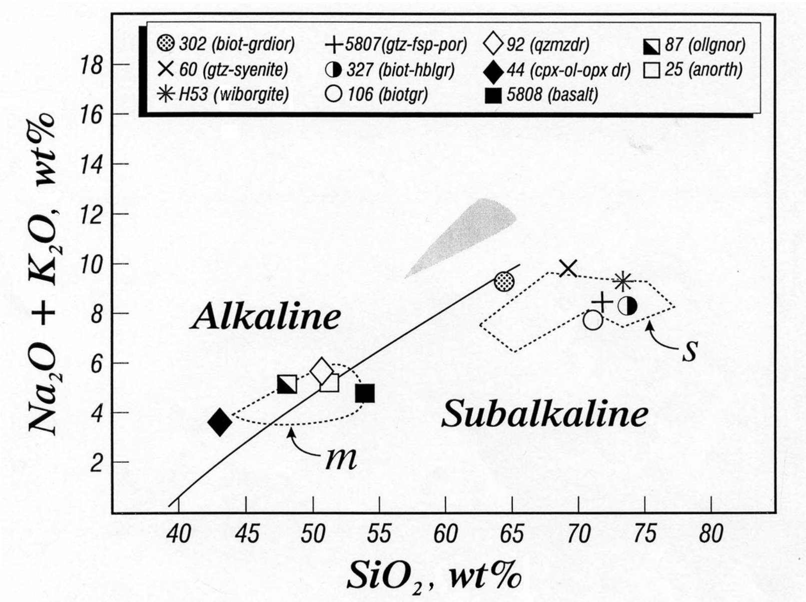

Fig. 2. Total alkali vs. silica diagram (Irvine & Baragar 1971) for six silicic and five mafic rocks of the Riga batholith and Estonian stocks. (See Appendix for sample list). Abbreviations: cpx, clinopyroxene; ol, olivine; opx, orthopyroxene; dr, diorite; lgnor, leuconorite; anorth, anorthosite; qzmzdr, quartz monzodiorite; biot, biotite; gtz, quartz; fsp, feldspar; por, porphyry; gr, granite; hbl, hornblende; grdior, granodiorite. Dashed contours denote the composition of the mafic (m) rocks associated with the rapakivi granites of southern Finland and the silicic (s) rocks of the Finnish rapakivi occurrences (Rämö 1991). Grey pattern denotes the composition of the alkali feldspar syenites of the Suomenniemi complex (Rämö 1991).

Kirs 1992). However, they do not reach the fractionation level of the Finnish topaz-bearing granites (Fig. 3) (Haapala & Rämö 1990).

The rare earth element (REE) compositions of the silicic rocks are shown in Fig. 4. The rocks are clearly enriched in light REE and show, in general, chondrite-normalized patterns similar to those of the Finnish rapakivi granites. The latter, however, have a bit lower REE contents and more gentle slopes of spectra. In detail, the Estonian granites from the stocks show slightly weaker negative Eu anomalies, suggesting that they are somewhat less evolved.

In the Rb versus (Y + Nb) and (K_2O + Na_2O)/CaO versus (Zr + Nb + Ce + Y) tectonomagmatic discrimination diagrams (Pearce et al. 1984; Whalen et al. 1987), the compositions of granites from the stocks and Riga batholith plot close to the Finnish rapakivi granites (Haapala & Rämö 1990; Rämö & Haapala 1995) and within the fields of within-plate or A-type granites (Figs. 5, 6).

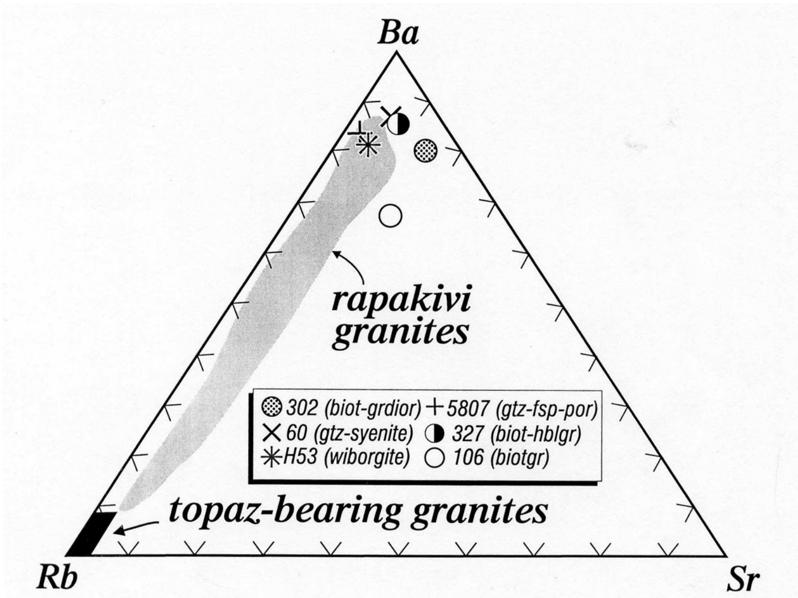

Fig. 3. Rb-Ba-Sr diagram for six silicic rocks of the Riga batholith and Estonian stocks. See Appendix for the sample list. Shaded area: rapakivi granites from the Wiborg and Laitila plutons; black area: topaz-bearing phases (both after Haapala 1988).

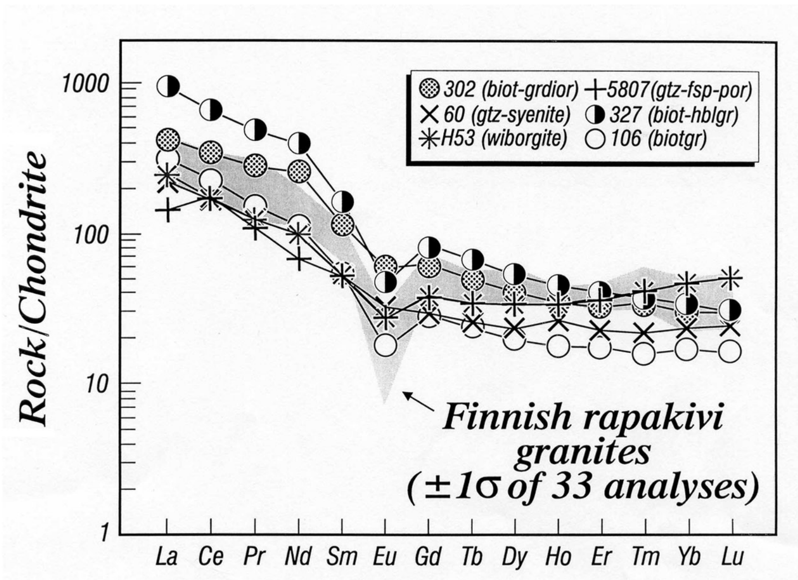

Fig. 4. Chondrite-normalized rare earth element plot of six silicic rocks of the Riga batholith and Estonian stocks (normalization after Boynton 1984). Rock symbols and abbreviations as in Fig. 2 and Appendix. Shaded area shows the range (as ±1σ about the mean of 33 analyses) of the Finnish rapakivi granites and quartz-feldspar porphyries (data from Rämö & Haapala 1995).

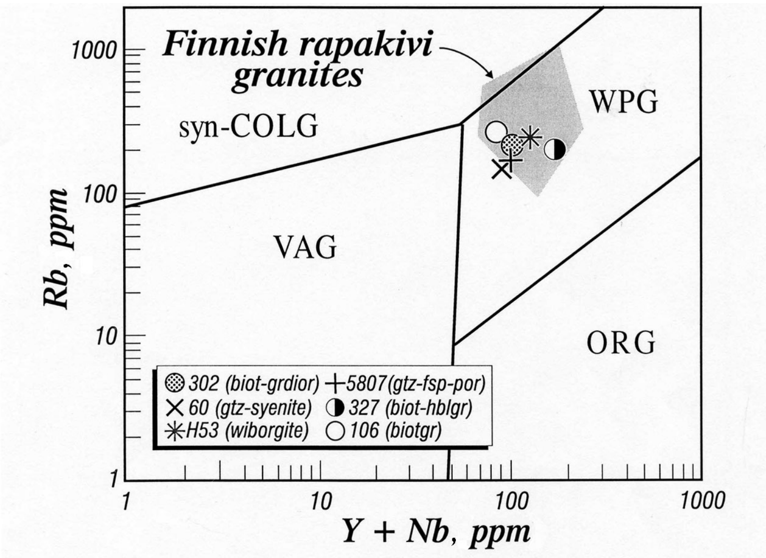

Fig. 5. Composition of six silicic rocks of the Riga batholith and Estonian stocks plotted in the Rb versus Y + Nb tectonomagmatic diagram of Pearce et al. (1984). Rock symbols and abbreviations as in Fig. 2 and Appendix. Shaded area: composition of rapakivi granites of southern Finland (Rämö & Haapala 1995). ORG denotes ocean ridge granites, VAG volcanic arc granites, syn-COLG syncollision granites, and WPG within plate granites.

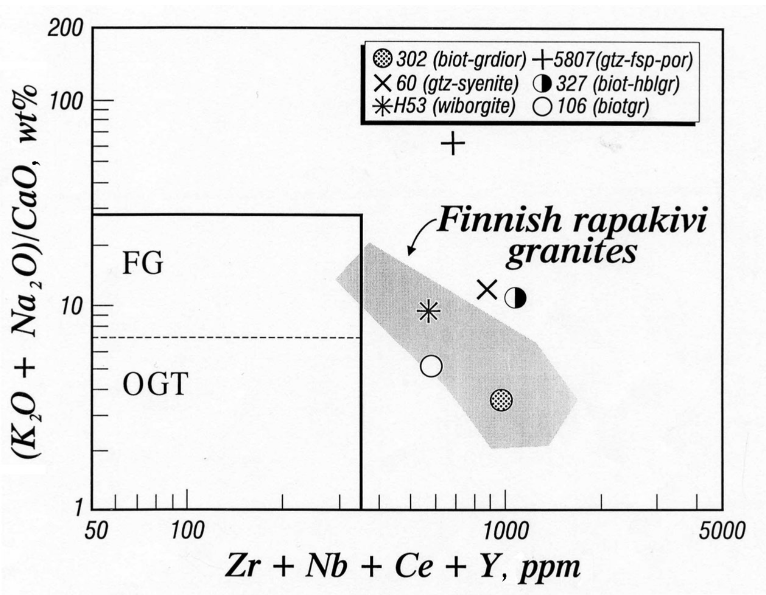

Fig. 6. Composition of six silicic rocks of the Riga batholith and Estonian stocks plotted in the $(K_2O + Na_2O)/CaO$ versus (Zr + Nb + Ce + Y) diagram of Whalen et al. (1987). Rock symbols and abbreviations as in Fig. 2 and Appendix. Shaded area: composition of rapakivi granites of southern Finland (Rämö & Haapala 1995). FG denotes fractionated felsic granites, OGT unfractionated M-, I-, and S-type granites.

Mafic rocks

The mafic rocks from the Abja stock and Riga batholith (except for the anorthosites of the Riga massif) show Fe-rich tholeiitic compositions and plot on the boundary between the alkaline and subalkaline fields in the total alkalis versus silica diagram (Fig. 2). All are hypersthene normative and show relatively high contents of TiO_2 (2.3–3.4 wt%) and high P_2O_5 (1.4–2.1 wt%). The Mg numbers (mol.100 Mg/(Mg + 0.85 Fe_{tot})) of the rocks are between 40 and 55 suggesting substantial fractionation before intrusion to their present level. This is in accordance with the low contents of Cr (up to 45 ppm) and Ni (20–50 ppm). An exception in this regard is the Aizpute two-pyroxene-olivine diorite with ca. 100 ppm Ni.

The REE contents of the mafic rocks are comparable to those reported from the mafic rocks associated with the Finnish rapakivi granites, except the quartz monzodiorite of the Abja stock which is strongly enriched in light REE (Fig. 7). The cumulate nature of the anorthosite of the Riga batholith is supported by its low total REE content and a Eu maximum (Fig. 7).

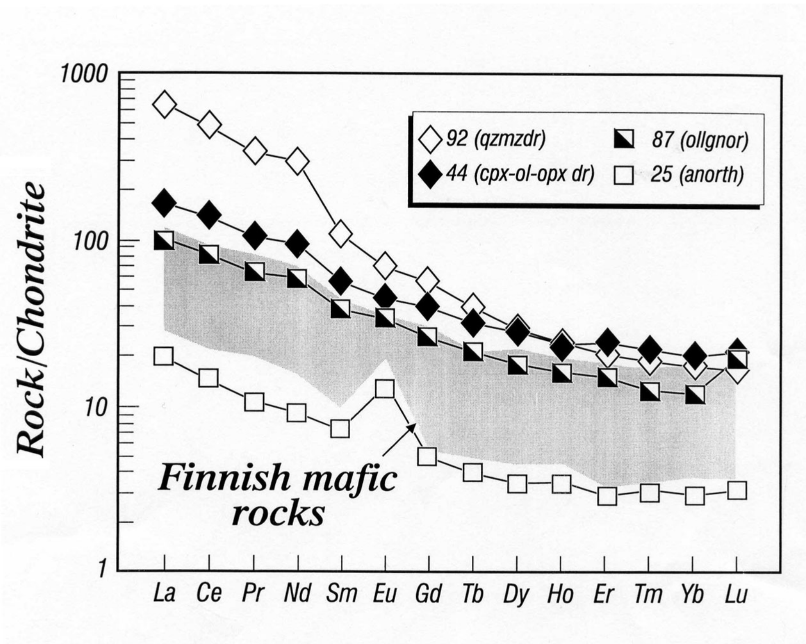

Fig. 7. Chondrite-normalized rare earth elements plot of four mafic rocks of the Riga batholith and Abja stock (normalization after Boynton 1984). Rock symbols and abbreviations as in Fig. 2 and Appendix. Shaded area: composition of gabbroic and anorthositic rocks associated with the rapakivi granites of southern Finland (data from Rämö 1991).

AGE AND SOURCES OF ESTONIAN ANOROGENIC ROCKS

Two zircon samples, one from the Märjamaa granodiorite and one from the Naissaare biotite-hornblende granite, have U-Pb zircon ages on the order of 1620–1630 Ma and are thus coeval with the rapakivi granites of the Wiborg batholith and its satellites (Rämö et al. 1996). The Abja quartz monzodioritic stock, with U-Pb zircon ages of 1635 ± 7 Ma (mafic rocks) and 1622 ± 6 Ma, (silicic rocks) (Kirs & Petersell 1994) also belongs to this group. The Riga batholith, on the other hand, is coeval with the rapakivi granites of southwestern Finland (e.g. the Åland batholith); zircons from a leucogabbronorite and a biotite-hornblende granite of the Riga batholith show U-Pb ages of 1576 ± 2 Ma and 1584 ± 7 Ma, respectively (Rämö et al. 1996).

Whole-rock isotopic data (Rämö et al. 1996) indicate an approximately chondritic source for the Nd in the mafic rocks of the Riga batholith and the Abja stock, and a Palaeoproterozoic (Svecofennian) source for the felsic rocks: the T_{DM} model ages of the felsic rocks range from 1890 to 2100 Ma. The Pb in the mafic and felsic rocks was probably derived from a source with relatively high long-term U/Pb (single-stage μ value ca. 8.2). The Nd and Pb isotopic compositions of the felsic and mafic rocks of the rapakivi complexes in Estonia and Latvia are largely similar to those of the Finnish rapakivi complexes (Rämö 1991). This shows that the lower crust and the subcontinental mantle are devoid of a (major) Archaean component in Estonia as well as northwestern Latvia (Rämö et al. 1996; see also Puura & Huhma 1993).

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APPENDIX

EXPLANATION OF SAMPLE CODES IN FIGS. 2–7 AND TABLE 1

327	biotite-hornblende syenogranite, first intrusive phase of the Naissaare pluton
106	biotite syenogranite, first intrusive phase of the Neeme pluton
302	biotite granodiorite, first intrusive phase of the Märjamaa pluton
92	biotite-hornblende quartz monzonite of the Abja pluton
5807	fine-grained quartz-feldspar porphyry from the Undva complex on the northern flank of the Riga batholith, Saaremaa
5808	fine-grained porphyritic basalt from the Undva complex on the northern flank of the Riga batholith, Saaremaa

H53	biotite-hornblende syenogranite (wiborgite) in the central part of the Riga batholith, Ventspils, Latvia
60	quartz alkali feldspar syenite in the south-central part of the Riga batholith, Edole, Latvia
44	clinopyroxene-olivine-orthopyroxene diorite in the southwestern part of the Riga batholith, Aizpute, Latvia
87	olivine leucogabbronorite in the southeastern part of the Riga batholith, Viesite, Latvia
25	anorthosite in the southeastern part of the Riga batholith, Kandava, Latvia

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Eesti kristalse aluskorra anorogeensed magmakivimid

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Fennoskandia paleo-mesoproterosoilisesse rabakiviprovintsi kuuluvaid fanerosoilise settekatte alla maetud Eesti kristalse aluskorra anorogeenseid plutoone esindavad hiiglaslik, põhiliselt küll Loode-Lätisse jääv Riia batoliit (pindalaga 250 × 230 km) ja viis graniitset (Naissaar, Märjamaa ühes oma Kloostri satelliitkehaga, Taebla, Neeme ja Ereda) ning üks kvartsmontsoniitne (Abja) štokk.

Riia batoliit, sarnaselt tüüpilistele Fennoskandia rabakivi plutoonidele, koosneb nii aluselistest kui happelistest magmakivimite intrusiividest.

Graniitsed štokid, mis geofüüsikalistel kaartidel väljenduvad gravi- ja magnetvälja miinimumidena, koosnevad mikrokliini fenokristallidega roosast, keskmisekuni jämedateralisest, osaliselt trahhütoidse põhimassiga, Märjamaa ja Naissaare plutoonis ka küünekivi sisaldavast biotiitgraniidist, mida kohati lõikavad apliitsed ja mikrosüeniitsed daikid.

Erandina on Märjamaa plutoon enam liigendunud, koosnedes oma keskosas anomaalselt kõrge magnetilisusega hübriidsest küünekivi granodioriidist. Ka Abja kvarts-montsodioriitne štokk on anomaalselt magnetiline, koosnedes rikkaliku hajuteralise apatiidi ja titanomagnetiidi sisaldusega tumehallist, massiivsest, kohati aga gneisilisest kivimist, mida lõikavad sentimeetri-detsimeetripaksused peeneteralise, kergelt porfüürilaadse plagioklass-mikrokliingraniidi sooned. Graniitide kivimit moodustavate, lantanoidide ja teiste jälgelementide sisaldused on sarnased Soome rabakivide vähem liigendunud graniitsetes faasides jälgitavatega. Märjamaa granodioriit ja Abja kvartmontsoniit on rikastunud Sr, Ti ja P poolest. Nii happeliste kui aluseliste magmakivimite Nd ja Pb isotoopkoostised sarnanevad samuti Soome rabakivikompleksides jälgitavatega, viidates Riia ja Abja plutoonide aluseliste kivimite puhul vahevöö kondriitsele lähtekivimile, graniitsete kivimite puhul aga paleoproterosoilisele (Svekofennia) koore lähtekivimile. Happeliste kivimite vaesustunud vahevöö mudeliline vanus (T_{DM}) kõigub vahemikus 1890–2100 miljonit aastat.